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# GEOLOGY AS A SCIENCE AND ITS PLACE IN NATURAL HISTORY[1]

by

G. L. Pospelov

## GENERAL CONSIDERATIONS

In recent years, geology has been a target or many critical observations, mostly "criticism from within", expressing the dissatisfaction of geologists with the present status of their science which lags behind practical demands, often confines itself to a superficial analysis of geologic processes without an adequate treatment of their essence, and inadequately reveals the evolution of the earth as a planet [1]. There is, however, another line of criticism, with regard to the interrelation of sciences and to the place of geology in natural history at large. This last criticism is part of a general discussion on the present status of science.

It is unfortunately true that little attention is given geology as a science, in that discussion. It is probably true that in the field of natural sciences, the earth sciences, including geology, have been given the least space in philosophical publications.

This means that geology has not yet attained its proper place in that field.

What is the reason for that? Is it the present status of geology or is its general status as a science? Are any of its aspects of interest to natural history as a whole?

It should be noted that deliberations on this subject, mostly oral discussions, have revealed the high esteem formerly expressed in publications, for geology as a science, as witness the observations by J. Bernal, an outstanding physicist and philosopher, in his book, "Science in the History of Society" [2]. This important and interesting work contains much valuable material on the history and differentiation of science and the problems of development, with an evaluation of individual disciplines in the over-all system of knowledge. In his section on "Science at the Present Time", J. Bernal makes the following general statement on the earth sciences:

"The place of earth sciences — geology, oceanography, and meteorology — is qualitatively different from that of the basic sciences — physics and chemistry. This is due to their lower degree of generalization, inasmuch as they deal with specific situations and periods rather than with establishing laws valid for all places and times. They contain more descriptive and historical elements and fewer logical and mathematical ones. In that, they are graphia rather than logia.

"For this reason, even if they have grown tremendously in their volume, the changes they underwent have been determined mostly by new technical methods and new ideas borrowed from physics and chemistry. The twentieth century has brought nothing to necessitate a radical revision of the principles of geology established in the nineteenth century" ([2], page 428).

This conclusion by J. Bernal — which, incidentally, is eagerly quoted in oral discussions on the future of geology — is not, strictly speaking, a general academic evaluation of earth sciences, or of geology, although it contains elements of evaluation and poses a number of general philosophical problems deeply affecting geology as a science. Because of that, this statement of J. Bernal is rather disheartening to geologists who read it to mean that the science of geology is exhausting its specific problems and possibilities.

I believe it, therefore, expedient to consider in more detail the topics touched upon by J. Bernal.

## DOES GEOLOGY STUDY THE GENERAL LAWS OF NATURE?

On the basis of J. Bernal's observation, this question can be rephrased as follows: is geology among those sciences characterized by a low level of generalization, not rising up to reveal general laws of nature?

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[1] O kharaktere geologii kak nauki i yeye meste v yestestvoznanii.

Geology is the science of the earth but in a sense it is a cosmic science, also. The earth is not the only planet in the universe, but one among many others. Whatever the variety of planets and of material, structural, and genetic types, they all represent qualitative variations of cosmic matter possessing certain general properties. Although we still are far short of knowing the general system of planetary types of the universe, we are witnessing the birth of a science of the structure and evolution of planetary worlds, i. e., planetology, based on data of geology and astronomy, with geology its main component. For the time being, the earth is the only planet where we can study the laws of structure and internal development of any other planet similar to it in properties and mass, with a certainty that these laws are not an exception but, on the contrary, the general laws of structure and evolution of all planets. Even now, the data of geology permit a comparative evaluation of the structure of and life on planets of the solar system. A graphic example of this are studies of present and ancient volcanism of the moon.

Having its foundation in the achievements of astronomy, for which electronics and rocketry open dazzling perspectives, and based on geology, planetology may attain a level where the knowledge of systematics and of general evolutionary laws for planets becomes possible. This is of an immense theoretical and practical value because planets are the basic generators and carriers of life in the universe, and their appearance is the most important stage in the evolution of cosmic matter and life. In this sense, geology, studying as it does the laws of structure and evolution of the planets, in the example of the earth, and the effect of this evolution on the origin of organic life and intelligent creatures, finds itself among sciences studying the general laws of nature.

The idea of the science of the earth as a discipline of cosmic science has long been familiar in the evolution of natural science. The discovery of the identity of terrestrial and cosmic laws of gravitation, and of chemical elements in the earth and in the universe — these and other great applications of earth science to cosmic study have long since laid a scientific foundation for the idea of uniform terrestrial and cosmic laws. As applied to earth sciences, this was especially well expressed by V. I. Vernadskiy who, in writing on this subject in his "Outlines of Geochemistry", stated that geochemical problems are inseparable from those of cosmic chemistry and that the chemistry of the earth is a manifestation of planetary chemistry [3].

But perhaps this unity of terrestrial and cosmic processes belongs solely to the field of physics and chemistry, whose general laws on earth are general laws of nature as a whole, and may not rightly be applied in the analysis of geologic laws of structure and evolution of the planets. What is more, perhaps geology should be regarded as a specific descriptive division of physics and chemistry, independent only until we have found our way in the physics and chemistry of the earth and finally reduce all geologic phenomena to physical and chemical processes which then can be used in expressing the general laws of planetary evolution.

These questions are not new and they concern other natural sciences besides geology. There have been many attempts to "reduce" chemistry to physics, specifically to quantum mechanics, biology to chemistry and physics, etc. [4, 9]. This is an old philosophical problem of the "reducibility" of various forms of the motion of matter to certain elemental or to a single initial and simple form of motion. It was attempted by the mechanists, in their time, and is being attempted by the latter day advocates of "reducibility" of all motion of matter to an "initial" physical motion [9].

The narrowness of such concepts has been well demonstrated by B. M. Kedrov, in the unsuccessful attempts to reduce the chemical form of motion to quantum mechanics. This "new knowledge" has not resulted, as yet, in any discovery of importance, in chemistry, while A. M. Butlerov's theory of chemical structure, which reflects the specific qualitative features of phenomena studied in organic chemistry, has made it possible to devise and synthesize thousands of new organic compounds [4].

The credit for a scientific formulation of the problem of multiplicity and unity in the principal motions of matter belongs to F. Engels. Recently, this problem has attracted the attention of Soviet scientists, in connection with working out the philosophy of natural science. Therein lies the basis for judging the place of geology in natural science, and the answer to whether geology does study the general laws of nature and what these laws are.

## GEOLOGY FORM OF THE MOTION OF MATTER

A classification of the infinitely diversified manifestations of matter by the principal forms of motion is the realm of a higher generalization of the material world [9]. Its basic premise is that motion constitutes a mode of existence of matter and that a knowledge of various forms of matter is the knowledge of various forms of motion and their relationship. In reducing his contemporary natural science to that basis, F. Engels identified several basic forms of motion, characterizing the basic forms of matter and the major disciplines treating them. According to Engels, they are the mechanical, physical, chemical, and biological forms of

notion [9, 10]. Modern natural science, having liscovered essentially new aspects of the mate-ial world, presents the philosophers and natu-al scientists with the problem of a further de-velopment and a partial revision of Engels' pre-nises on basic forms of the motion of matter 4, 7]. This problem was a principal subject of discussion at the All-Union Conference on the Philosophy of Modern Natural Science [9].

It is too early to speak of the modern theory of basic forms of the motion of matter: it is nerely in a stage of inception. It has become clear, however, that there are several trends along which the development of this theory can and must proceed. Basic forms of the motion of natter cannot be reduced to a single series. There appear to be several such series, in com-plex relationships to one another. Specifically, here are universal forms of motion, unknown to Engels, and manifested in the polarization of natter in physical fields (gravitational, electro-nagnetic, nuclear, etc.) and into the corre-sponding elemental particles [8]. It has been proposed to classify such forms of motion in a special group of subatomic [4] or "simplest" notions [8].

On the other hand, there are a number of enetic forms of motion which are modes of xistence for compound material units, from tomic to the largest cosmic systems. They are he result of a complex interaction of simple to nore complex motions, up to universal forms, which cannot be reduced to a simple sum of arious interactions, specifically those between he universal "elemental" forms of motion. While including the latter, they also represent ualitatively different complex forms of motion, ot universally present as interlocking "physical ields" but presenting rather the most character-stic, immutable, endlessly recurring in an in-nite material world, general — and principal - forms of the motion of matter.

These forms of motion include all those ormerly identified by F. Engels, insofar as e regarded them as modes of existence of toms, molecules, and masses of the substance f albumens. In this differentiation, however, . Engels, while separating the biological form f motion from inorganic atomic-molecular notion (the physical and chemical), did not dif-ferentiate, strictly speaking, the inorganic nacromotion, confining himself to its mechani-al form. He has demonstrated that the mechan-ical form of motion is implicit in all micro- and nacro-bodies, thus presenting an external spect, or example of any motion [4, 8].

The problem of differentiating inorganic nacromotion into basic forms of motion has not een properly developed, as yet. However, B. I. Kedrov has proposed geologic motion as one f the basic forms of inorganic motion, meaning special synthesis of lower and simpler forms of the motion of matter (mechanical, physical, and chemical), characterizing such modes of matter as minerals, rocks, and more complex geologic formations [4].

He recognized the geologic form of motion as a primary attribute of the lithosphere, hydro-sphere, and atmosphere of the earth, character-ized by definite relations between these spheres and within them (including the biosphere).

Such a somewhat limited interpretation of the geologic form of motion has aroused doubts of some philosophers (for instance, M. N. Rutke-vich, [8]) as to whether this "interlacing of physiochemical processes which takes place in the earth's crust" should be assigned to basic forms of motion, inasmuch as it does not "con-stitute the foundation of matter". This doubt is justifiable if the definition of the geologic form of motion is confined to the earth's crust, con-sidered apart from the evolution of the earth as a whole and apart from its relation to the uni-verse. However, inasmuch as the earth is a planet, one of the series of units of cosmic matter, its origin and existence lie within the scope of the "foundation of matter". Conse-quently, the form of motion defining the ex-istence of planets as qualitatively individual for-mations cannot be excluded from the principal forms of the motion of matter. This is a planetary (geologic, in a specific case) form of the motion of matter, belonging to a series of basic cosmic forms of motion of matter whose genetic sequence can be represented by basic cosmic units "producing" one another. In a very simplified way, this series can be represented as nebulae — stars — planets.

The members of this series are contrasted with the internebular and interstellar cosmic space, as "particles" are contrasted with a "field". Such a genetic series characterizes a definite trend in the evolution of cosmic forms of the motion of matter. Its open-end aspect means that the series is incomplete, represent-ing but a portion of the universal vortex of matter, with the position of the extreme mem-bers of the series indicating definite qualitative spurts in the evolution of matter. In nebulae, this probably is the change of radiation energy to the corpusclar (i. e., a change of cosmic radiation to particles of cosmic matter which forms nebulae of a definite, "primordial", genetic type). In planets, it is a change of another kind.

In considering the geologic form of motion in a genetic series of the main forms of motion of matter (from lower to higher), B. M. Kedrov noted that it occurs at the polarization of matter into organic and inorganic. Such a polarization is not present with lower forms of motion (sub-atomic, atomic, molecular) [4]. This is an important fact characterizing a transitional and specially oriented evolutionary trend for the

planetary form of motion, toward a polarization of matter into organic and inorganic. This potential trend is not necessarily culminated in a realization of such polarization in every case but is so realized under certain conditions, which then represent a main qualitative spurt in the development of the principal cosmic types of matter, at the planetary "end" of a cosmic series.

Thus the planetary, more specifically, geologic, form of motion is a prerequisite for the origin and development of a biologic form of motion. That, however, does not exhaust their relationship; a biologic motion is a component of the geologic.

As emphasized by V. I. Vernadskiy, the problem of the origin of life on our planet, from a geochemical and geologic point of view, is not the synthesis of an individual organism but rather the origin of the biosphere greatly affecting the chemistry of the entire earth's crust. V. I. Vernadskiy believed that the energy effect of living matter as a store of solar energy, on the development of geologic processes is one of the deepest manifestations of life which science has studied [3].

On the other hand, evolution of life comprises geologic motion as reflected in the structure, composition, and the nature of evolution of the organisms and their associations. The history of the development of the organic world is the history of the development of the planet refracted in the biosphere, the result of a deep penetration of the biological form of motion by the geologic. Understanding this polarization of motion into biologic and inorganic, and understanding the general laws of their mutual interpenetration, is one of the most important problems of natural history, particularly of geology, and most specifically of biogeology, including paleontology, biogeochemistry, and other sciences.

However, the general evolutionary trend of the planetary form of motion is not confined to polarization of matter into organic and inorganic forms. Implicit in that form of motion, as in any other principal form of group and complex motions of matter, are other most important trends, determined by a progressive movement of matter from lower forms to higher. In a most general way, this can be expressed, on one hand, as a complication in the internal structure and composition of a material entity, in the course of its development (internal differentiation); on the other hand, it is an intensification in the interrelationship between manifold phenomena and a development of those general aspects of such interrelationship involving the entire material system, as a whole (general coordination).

Higher forms of such differentiation and coordinations are achieved in the organic world. Live organisms are the most complex internally differentiated entities endowed with the highest forms of coordination of processes which take place in them. All specific changes in organisms, especially in higher ones, affect in one way or another the entire organism or are a product of processes affecting all of it.

Such higher forms of internal differentiation and mutual coordination are not attributes of the inorganic world; however, in the course of evolution of actively developing inorganic worlds there is an intensification of their internal differentiation and of the correlation of motion, up to a certain definite maximum which is at the same time a culmination of the given material system.

With this maximum attained, the next stage is either the change to a qualitatively new form of active motion (for example, from star to planet) or a slackening and extinction of internal processes. "Self conservation" of the cosmic form of motion and a cessation of the active internal development in a cosmic body are attributes of terminal stages in the evolution of planetary worlds — and one of the specific attributes of the planetary form of motion. Planets, however, have an "ascending" motion of their own. It is expressed, among other things, in the emergence and multiplication of planetospheres (geospheres) and other material structural units in the earth differentiation into continents — oceanic troughs, platforms — geosynclines, plutonic-volcanic processes, etc.). On the other hand, it is expressed in the development of complex internal interrelationships between various planetary processes, which attain a definite maximum in a period of culmination of the internal evolution of the planet. The highest manifestations of the planetary form of motion of matter are those motion complexes marked by the highest degree of coordination and interrelationship affecting the entire planet or large parts of it. Under terrestrial conditions, this is expressed in elements of a general periodicity and rhythm in geologic development; in the stage-by-stage progress, complexity, and zonation of geologic processes involving immense provinces; and in the geochemical evolution of some geologic processes, common in the history of our planet (e. g., magmatic ore formation) and suggesting a possible participation in them, of deep parts of the earth, etc.

The evolution of internal differentiation of the planetary form of motion is directly related to the advent of stable polarization of matter into organic and inorganic, possible only when planetary substance has attained certain types and degrees of differentiation. This implies a number of important specific features of planetology, i. e., geology as a science, and problems in the field of general science.

It should be noted, first of all, that the planetary form of motion, as a form of existence of the planets, is as infinitely diversified, internally, as any other basic form of motion of matter. Each planet has a complex of macro- and micromotions of its own, characteristic of it at a given time and in the general historical plan. At the same time, the planetary form of motion, as a whole, comprises all forms of movements typical of that form of matter. Together, they make up their genetic associations responsible for the principal content of that form of motion and representing its principal and universal modes.

Each principal mode of the planetary form of motion represents a complex of motions embracing the widest possible circle of its essential interrelationships. For example igneous activity is one of the probable principal modes of the planetary forms of motion of the earth as well as the moon. As a form of the most energy-consuming planetary motion, igneous activity is not merely individual volcanic and plutonic phenomena constituting its elements; it is the totality of all phenomena pertaining to igneous activity, from its origin to the ultimate result, their interrelationship and interaction as part of a structurally material and historic whole. It is an understanding of the essence of this complex as a whole that constitutes the ultimate goal of the knowledge of the igneous form of planetary motion.

Geology has come to differentiate a number of macro- and micro-forms of geologic movement, characteristic of the entire geologic evolution of the earth. Such are mineral-making, sedimentation, igneous activity, metamorphism, faulting, epeirogenesis, folding, etc. It is possible that they belong among the very common, and some among the principal, forms of planetary movement in general, now being studied in part on earth and soon to be studied more and more on other planets. The knowledge of these and other principal forms of geologic planetary motion as a whole, along with discovering new forms of such motion, is one of the main tasks of planetology, of "cosmic" significance.

A solution to this problem is inalienably related to analysis of the general laws of differentiation, complication, and multiplication of the types of planetary forms of motion in the course of planetary evolution, and to the emergence of those "critical" phases of that motion where a stable polarization of matter into organic and inorganic is initiated.

A solution to the problems of a growing differentiation of planetary forms of motion is just as inalienably related to the problem of a growing coordination of planetary motion, the emergence of higher degrees of coordination, the aspect of the culmination of the planetary evolution, and its decline.

An internal differentiation of the earth into geospheres, probably one of the general modes of the planetary forms of motion, leads to the emergence of different motion complexes for each geosphere, the core, the mantle, and the crust, with all complexes tied to one another in a definite way. This is manifested in the general trend of material-structural changes in a planet and in the phenomena of general coordination of certain geotectonic and geochemical processes, as mentioned above.

Solving these problems calls for an understanding of the planets as a whole, in their relationships with the cosmos and in their specific features characterizing them as actively developing (or developed) cosmic systems. This is the basis of planetology as a synthesis of the sciences of planets. One of these sciences is geoplanetology (geology + astrogeology + geography + oceanography + paleontology, and to some extent biology. In a nascent stage are lunar and Martian planetologies, followed by a roster of nascent planetologic sciences. For the time being, they deal with the solar-system planets; the time will come when they will go beyond that.

The supreme results of a combined effort of these sciences is the knowledge of higher forms of planetary motion, the active self-development of the planets in their union with the cosmos. This result will be attained only at a certain level of knowledge of the structural-material differentiation of planets, as well as of forms of planetary coordination of processes running their course within them. It is probably true that geology has already reached that minimum knowledge of the planetary form of motion on earth, which visualizes the latter as a quite complexly-differentiated planet with an active internal self-development. It can be stated of modern geology that it has established, in the example of the earth, certain types of planetary forms of motion of matter; they are revealed in the general laws of structure and development of this planet possessed of an active internal self-development. It has also established that one of the principal forms of geologic movement on earth is a biologic motion of matter, thus demonstrating that man originated when the latter motion had acquired the attributes of the former, on a planetary scale. All this places geology, despite the serious shortcomings of its present status, in the vanguard of natural sciences and marks it as a study of general laws of nature.

## GEOLOGIC METHOD AND ITS PLACE AMONG OTHER METHODS OF NATURAL STUDY

The reducibility of geology to physics and chemistry also involves methods of study. Geology, with study methods of its own, also makes extensive use of those of other sciences, mostly

physics and chemistry. The physical method of studying natural phenomena, with the extensive use of mathematics, now is widely shared by all fields of natural knowledge and has become the leading one in many studies. This method has been more and more appropriated by geology, providing it with a new store of facts and new means for a precise study of the earth, thereby stimulating the further progress of geology as a science.

What then is the future of the relationship between geologic and physical methods of study? Is the geological method one of those which may exhaust its possibilities and become an auxiliary to "more precise" physical and chemical methods? This is not a rhetorical question, inasmuch as it is often posed in critical observations on geology and in prognostication of its future, as witness the interesting and important article by V. V. Belousov on the present status of theoretical geology [1]. In criticizing the narrow scope of methods of present-day geology, that author states that although much can still be done by the standard methods of geologic study "in refining the sequence of geologic events and for a better understanding of regularities in their spatial and temporal relationship" (italics mine, G. P.), the very fact that geology deals with physical and physiochemical phenomena will lead to physical and physiochemical methods replacing the less accurate geologic methods of study, which will determine the further achievements of geology.

Strictly speaking, that article does not present a general evaluation of the geologic method, its future, and the basic relationship with methods of physics and chemistry, although it carries elements of such evaluation. It regards the geologic methods as declining in development, applicable only to refining and perfecting what is already known, while the future of geology is tied basically to the methods of physics and chemistry. The problem is not a simple one and requires more careful consideration.

A method is a way of studying leading to an understanding of the objective world. The geologic method, in its most general aspect, can be defined as a method of representing the geologic form of the motion of matter through a consecutive revelation of structural-material and energy properties of the earth, in their spatial-historical and genetic relationships. This very definition implies that the geologic method is inexhaustible and that any other methods of natural analysis, as applied to the knowledge of an inexhaustible geologic form of motion, unavoidably take on specific features of the geologic method and become its components. Their value may be paramount in determining certain properties of the earth, considered apart from general geologic interrelationships, but it cannot become universal inasmuch as a universal representation of each of the principal forms of the motion of matter can be accomplished only by a method peculiar to it.

Specific features of the geologic method are determined first of all by the nature of those geologic elements which are the objects of the study. Such natural geologic elements as minerals, rocks, formations, geologic structure, geotectonic stages, volcanic centers, the geosphere, etc., can be studied jointly with most diversified methods. When, however, a study object is represented by geologic elements in their geologic relationship with other elements within the context of their geologic history, the entire complex of methods is subordinated, in the final account, to the geologic method and merge in it as parts of a whole.

Such geologic methods as those of mineralogy, lithology, petrography, stratigraphy, the study of facies and formations, structural geology, geotectonics, etc., are quite complex. They include non-geologic methods as well as elements borrowed from each other. For example, the petrographic method with its microscopy, chemical and physical analyses, etc., makes extensive use of physical and chemical techniques. Still, all such techniques are subordinate in it to the geologic method, and have a geologic aspect, culminating in a petrographic method. This is true to a varied extent for other geologic methods. The structural and geotectonic analyses of the crust include elements of geometric (geometric types of deformation) and graphic or statistical constructions (diagrams of fracturing; tectonic zones, statistically identified from linear concentrations of magmatic bodies and ore deposits, etc.), as well as purely mechanical techniques (analysis of tectonic stresses and deformations), elements of solid-state physics (differentiation of "competent" vs. "incompetent" beds, plastic vs. brittle rocks, unconsolidated vs. consolidated sequences) etc.

Obviously, it would be wrong to regard all these study methods as independent of the corresponding geologic methods. It is also obvious that, as long as techniques of other methods are used in geologic methods, the development of the latter is inalienably related to the improvement in the former and to their ever-growing importance in geology.

Consequently, an intensification of physical and chemical methods in geologic study by no means "exhausts" the latter. On the contrary, it demonstrates progress in geologic methods of nature study, and their rising to a higher degree of excellence. Take stratigraphy as an example. The development of physical and chemical methods of absolute-age determination has to some extent revolutionized stratigraphic dating of geologic formations and has considerably broadened its scope. At the same time, it is quite obvious that all speculations

about a complete "substitution" of absolute dating (in years) for a relative stratigraphic dating has turned out to be groundless: the preservation of a radiogenic equilibrium between radioactive elements and the products of their decay, which is the basis for absolute dating, requires a set of objective conditions often either completely or partially absent in nature. For this reason, the absolute age figures reflect at times some peculiar features of the rock origin and the history of their alteration, rather than their age. It has become quite clear that the further development of stratigraphic analysis as a whole depends on both absolute and relative dating and on establishing proper mutual relationships. This example is a fair warning to those students who believe that geologic methods can be fully replaced by those of physics and chemistry.

Some authors believe that visual observations are the most important component of the geologic method [1], its principal arm. This is true to the same extent that physical and chemical observations are made with special instruments. However, neither visual observation (more properly, sensual perception) nor the use of "instruments" is in itself characteristic of a study method, but rather is common to all methods; consequently, a more intensive use of instruments in geologic observation is not at all the substitution of a physical method for the geologic. The essence of a method is not in the technique of observation but in a specific representation of the laws of nature peculiar to one or another form of the motion of matter.

The intensive introduction of physical and chemical methods in other fields of natural science, including geology, has led to the emergence of allied disciplines and new methods of study. The development of the physical and physico-mathematical method of earth study has introduced a new science of geophysics, while progress in the study of the chemistry of the earth has brought in geochemistry.

The history of their relations to geology is rather complex, especially for geophysics. Its physical and mathematical methods and problems were so self-sufficient, in the beginning, that this led to a certain independence of geophysics from geology and to a somewhat speculative approach to many joint geological and geophysical problems. Some elements of that break have persisted to this day, to slow down the progress of both disciplines. This is also true for geochemistry, to a smaller extent; here, too, there is a tendency for a break with geology and for the development of chemistry proper.

This break should not be regarded as a fortuitous phenomena, evil by its very nature. The establishment of geophysics and geochemistry as sciences with methods of their own has promoted the development of physical and chemical methods of little interest to other disciplines. However, this greater emphasis on exclusively physical and chemical problems has been accompanied by the deemphasis of geology by geophysicists and geochemists, the deemphasis being intensified to no small extent by the fact that "the number and measure" which they applied to the mass of the earth and its components have acquired in geophysics and geochemistry a somewhat independent meaning of their own. Undoubtedly, this was a "hypnosis" of precise figures and calculations allegedly fully capable of replacing geologic facts and a properly geologic solution to a problem.

On the other hand, geologists, because of tradition and the nature of geologic training, showed little inclination to meet geophysicists and geochemists halfway, because that would require a supplementary mastery of data and methods comparatively remote from those familiar to them. It took some time for a rapprochement of geology with geophysics and geochemistry, and not until it became clear that the essence of geophysics and geochemistry was not merely in obtaining proper physical and chemical data but in geologic interpretation of this data. Without such an interpretation, all these data are but a product of a strictly physical and chemical study of the earth's mass and substance, on the same level with any other physical and chemical investigations of matter, conducted to obtain general information on nature.

Confining oneself to a mere gathering of facts is to represent the earth as a sum of physical and chemical indices devoid of a natural historical content. In that event, geophysics and geochemistry will not be different from general physics and chemistry, since they, too, deal ultimately with materials largely of terrestrial origin. However, geology becomes the primary factor as soon as data of geophysics and geochemistry are subjected to a geologic interpretation. It turns out quite often that only by applying a joint geophysical and geochemical method does the true meaning of these data become clear (and at that, not always, by far, at the present level of science); otherwise they merely characterize a fairly large circle of concrete phenomena. It follows that geophysics and geochemistry are essentially geologic sciences oriented toward a study of the geologic form of the motion of matter. Geophysical and geochemical methods are special geologic methods, inseparable from other such methods and differing from them only by the greater emphasis on physical and chemical study techniques. When some geophysicists and geochemists forget that they are geologists first, they promptly become plain physicists and chemists who have forsaken the special aspect of their particular field, and have lost the

guiding thread to an understanding of the earth and its structure and evolution.

## SPECIFIC FEATURES OF TWENTIETH CENTURY GEOLOGY AND PROSPECTS FOR ITS OVER-ALL DEVELOPMENT

There have been no discoveries in twentieth century geology of the magnitude of those in physics. Still, geology does not deserve, by any means, the less than modest rating assigned to it by J. Bernal. In his "Science in the History of Society" [2] he states that geology as a science is based on principles of the nineteenth century and has grown largely quantitatively, "gigantically in volume". As a matter of fact, the twentieth century changes in geology testify to sizable qualitative advances in that field.

One of the objective indices of geology as a science is its enormous practical achievements, brought about not only by new techniques and a broadening of exploration work but by new scientific achievements, as well. Thanks to the latter, geologic forecasting has come to occupy an important place in the field of exploration, along with an initiation of the theory of a regular distribution of mineral resources. Incidentally, that theory has been systematically developed largely in the U. S. S. R. where geologists have access to all subsurface data of their land and where a joint method of geologic study of this planet prevails.

Geology, along with other natural sciences, has preserved the basic principles established in the initial stages of its development; at the same time, it has continued improving them. For example, the important geologic principle of actualism has been supplemented by the principle of forward motion; as a result, an essentially new historical principle has been formulated in geology.

Other important trends have been initiated; some of them develop ideas long known, while some others are the result of an analysis of new scientific data; for example, that recently formulated by N. S. Shatskiy and A. V. Peyve: the principle of heredity in tectonics [5], appears to be a general geologic principle. This principle stresses the broad development of hereditary phenomena for movements in old structures, the inheritance of old types of structures by new ones, a recurrence of physical features in superimposed igneous processes, hydrothermal activity, etc. The heredity principle, as based on facts of recurrence in geology, has some features in common with actualism; in characterizing but a single aspect of the development, it is in contradiction to another aspect which reflects the trend of the change, the crossing of superimposed phenomena, and the replacement of the old by the new. Thus, there emerge in geology ideas reflecting the inner contradiction of the evolutionary process and characterizing the elements of polarity in geologic phenomena.

Quite typical of present-day geology is the development of a number of related methods and theories, based on a certain common premise which can be named the principle of multistage realization of phenomena. According to it, geologic phenomena are joined to one another in regular complexes of various orders, forming in turn regular series.

One of the main achievements of geology based on this principle is the formation method and the theory of geologic formations, still in an initial stage but already gaining in stature. It has been long noted in geology that stratified and extrusive rocks, and ore deposits are not fortuitously distributed but rather form certain natural complexes and combinations. However, only in the last few decades has it been established that such an arrangement is a more or less general rather than a specific attribute of the crust, characterizing natural gradations of the group relationship for geologic processes; because of them, the crust turns out to be differentiated into peculiar geologic "atoms" and "molecules" of various types definitely related to one another in space and time.

The theory of formations is usually understood to mean a formulated concept of multistage sedimentary and sedimentary-volcanic stratified sequences (formations, groups of formations, and formation series of N. S. Shatskiy, L. B. Rukhin, N. P. Kheraskov, V. I. Popov, and others). In addition, there have appeared ideas of other formation types and geologic complexes and independent theories on them. Such are the igneous formations and formation series (of M. A. Usov, Yu. A. Kuznetsov, etc.), ore formations, igneous complexes (of G. D. Afanas'yev and others), structural igneous complexes (of Yu. A. Bilibin, etc.), multistage igneous provinces (G. L. Pospelov), complexes of related endogenic deposits and igneous rocks (petrometallogenic series of Kh. M. Abdullayev), genetic series of deposits, etc. In the process of formulation are generalizations on tectonic complexes and series, and many similar concepts whose number is growing rather rapidly. As a result, these assorted theories begin to be synthesized into a general theory of multistage geologic complexes of various types; their appearance has been accompanied by new geologic study methods and has brought about a thorough revision of many old ideas and principles of geology. The birth of this theory marks the advent of a new and higher stage in the development of geologic knowledge; it was initiated largely after the war, with Soviet geology being the main factor in its development.

A broadening of the idea of geologic complexes

om a regional to a global scale has led modern eology to the development of general concepts n global terrestrial structures reflecting all e processes which affect the earth as a cosmic ody. Problems of the continents and oceanic oughs, of global linear transverse structures neaments of R. S. Sander), a global cyclicity geologic and climatic-geologic processes, c., begin to fall into the general problem of obal earth processes as qualitatively differt forms of geologic motion. The global spect of this motion marks the earth as a osmic body related to the cosmos and affected it, and undergoing general internal changes a cosmic (global) scale. The successfully eveloping new science of astrogeology has been unded on this base.

The establishment of concepts of a qualitavely different global form of geologic motion is presented in a new light the problem of elationship between global, regional, and cal developments of the earth, as that of ultistage complexes closely related to each her in a single complex process, at the same me of discrete nature. This problem begins acquire to some extent points common with at of a quantum nature, discrete aspect, and scontinuity of physical quantities charactertic of microbodies. It is possible that a udy of multistage geologic complexes will ad to the discovery of "quantum type" phenomna in the macrocosmos. That may be the benning of discovering basically new laws not ly in geology but in physics.

The multistage aspect of geologic phenomena various magnitudes, which has long been oted in isolated instances (especially in such rocesses as the various types of folding), gins to take on the aspect of a general regurity encompassing a broad circle of phenomena hich may be grouped in genetic series of rious magnitudes (at times from elemental to obal). A good example of that is the multiage nature of intersecting linear structures, om the all-pervading network of cleavage actures to criss-crossing systems of global neaments ("geotectonic lattice", [6]), which tract the ever-growing attention of geologists.

Based on global problems and on their relanship with local problems of evolution of the rth, are the ever stronger ties between geogy, geography, oceanography, meteorology, d astrogeology — in other words, all scices of the earth, slowly but surely uniting to a single compound science of geoplanetogy.

In connection with the twentieth century delopment of a joint method, and with the nergence of new ideas of various multistage ologic complexes, the problems of genetic d paragenetic relationships between the enomena of genetic and paragenetic systems have become especially important. In the twentieth century, the concept of paragenesis — the connection between related phenomena — has stepped beyond the narrow confines of mineralogy and into the wide open spaces of geology and has become the basis of the theory of geologic formations, metallogenic complexes, etc. It pervades the entire problem of relationships between igneous activity and mineralization, between metamorphism and tectonics. This problem of relationships between genetic and paragenetic ties and systems now poses one of the most urgent theoretical problems in geology, among those which guide geology to ever more general solutions of its problems, from the near-surface layer of the crust down to unfathomed depths.

The phenomena of cross-relationships between geologic processes and the nice regularity of these processes over immense areas and during long periods, begin to loom as a result of broad and complex modern geologic generalizations, and present a majestic sight. It makes one ponder the basic principles of geology and that circle of ideas in the field of physics which guide it. The many unexpected discoveries in the realm of terrestrial space, recently made by means of artificial satellites, and particulary of the first cosmic rockets, make one cast a troubled eye to the deeper reaches of the earth of which we now know incomparably less than of the nearest cosmic spheres. This feeling of the proximity of great discoveries in the earth's interior is very intense with those who follow the mighty strides of modern geophysics. The unavoidable advent of such discoveries directly stems from the data of present-day geology which suggest the presence in the earth of such processes and of "regulators" and "condensers" of geologic energy, etc. [7] that go far beyond the geophysical data on hand and have no satisfactory theoretical explanations.

As a result of these discoveries, twentieth century geology has come face to fact with an understanding of the higher type of geologic form of motion, i. e., an understanding of the active self-development of the earth. The present stage in this field of study is marked by intensive work on the problem of group relationships between geologic processes in the earth; therein lies its fundamental difference from nineteenth century geology. In the nineteenth century, geology had but a poor concept of internal relations of geologic processes and freely fitted them in the framework of largely mechanical relationships. It obtained satisfactory explanations for its discoveries in simple premises of nineteenth century physics and chemistry, largely in mechanics.

Twentieth century geology, having discovered the high complexity in the interaction of geologic processes, is rapidly freeing itself of its former mechanistic views and is approaching

the new boundaries of its history. Some critics interpret those temporary theoretical difficulties which it is experiencing now as a crisis in geologic science. As a matter of fact, there is no crisis in geology, as witness the uninterrupted chain of discoveries of ever new regularities in the complex group development of the geologic process.

Geology finds itself at a transition stage leading to a major qualitative leap in development, and its difficulties are those of growing pains. The extant concepts of the physics of the earth are inadequate for an interpretation of the regularities discovered. The geologists begin to realize to an ever greater extent the limitations of physical knowledge with which they operate, because modern physics has not been adequately applied to the needs of geology. Suffice it to cite the neglect of the physics and chemistry of surfaces, in theoretical geology, although surface phenomena are tremendously important in terrestrial processes. Almost utterly unknown in geology is the modern theory of catalysis, although there is evidence of catalytic phenomena in geologic processes.

Especially difficult is the problem of the types of geologic energy. In analyzing geologic processes, geologists have labored mightily and successfully to prove the enormous importance of temperature and pressure in geologic processes. On the other hand, they have accomplished very little toward uncovering evidence of and the effect of electric fields in those processes, despite the object lesson of other natural scientists who have discovered the outstanding importance of electricity in phenomena of interest to them. Whenever geologists leave the macrocosmos and the geochemical relationships of atoms and molecules, they practically lose all interest in electricity. To be sure, a new division of geophysics, geoelectrics, has been shaping up; but its place is a modest one, for the time being, and it appears to be even less related than the other divisions of geophysics to the problems and methods of geology. Thus the science of electricity (including electrochemistry) is still outside the circle of the main interests of theoretical geology which only now is approaching the problems of electrology.

A broadening of the physical and chemical base of geology through its cooperation with present-day physical and chemical sciences will lead geology to a rich fount of discoveries and to abandoning many familiar and oversimplified concepts.

The penetration of deeper reaches of the earth by the ever more powerful tools of geophysics, especially in super-deep drilling now initiated on this planet, and the more detailed historical, physical, structural, and genetic analysis of geologic phenomena all lead geology along the path of knowledge of the crust as a peculiar "boiling layer of the earth", endowed with the complex nature of its general geologic "boiling" [6]. A detailed knowledge of the crust as a whole has been made imperative by an increase in practical demands on geology and by the necessity for solving practical problems formerly unknown.

The present status of geology enables it to cope relatively easily with practical tasks of exploring and evaluating mineral resources. In geology of the near future, this task will acquire a new meaning, in connection with the study of natural productive forces in the deep interior of the earth. At the same time, geology will face new problems in connection with a geophysically substantiated utilization of the geologic energy of the earth. The first stages of this work are already underway. There is more then one power station operating on the body energy of the earth. However, neither geology nor geophysics possesses more than preliminary data on this energy and on its forms adaptable for practical use. It appears that a complex and zonal evolution of various types of energy takes place within the crust, and it is not improbable that electricity rather than temperature will become in time the object of study of its inexhaustable and mighty energy, in our quest for an understanding and utilization of the activity of deep-seated "hearth zones" of the crust [7].

A penetrating and comprehensive study of the diversified energy system of the earth, along with its geologic evolution, specific features, distribution, concentration, discharge, and changes from one form to another, will probably lead in the future to the emergence of new practical geophysical problems. Among them may be the problem of controlling certain geologic processes, for example, by using the critical states of various energy "hearths" for converting some forms of geologic motion to others. Today, this is scientific fantasy, but tomorrow it may become an object of scientific study and of technologic exploration which will come to geology for a highly developed theory of the earth.

The entrance of man to the cosmos has opened vast possibilities for geology as planetology. A discovery of planetologic processes, either different from or similar to those prevailing on earth, will undoubtedly broaden the scope of our knowledge of the types and essence of a planetary form of motion and will lay the foundation of planetology as a new science of the twentieth century, born in geology. On the threshold of these great events, geology will proudly affirm that even as terrestrial atoms have provided physics and chemistry with a key to the knowledge of cosmic physics and chemistry, so the earth opens up the path to an understanding of the structure of and life on the planets of the universe.

In conclusion, the author expresses his deep ratitude to D. I. Shcherbakov, A. L. Yanshin, . A. Trofimuk, Yu. A. Kosygin, F. N. Shakhov, I. Matveyenkov, V. A. Kuznetsov, and to all ose comrades who have given much valuable dvice and many suggestions for this work.

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# THE STAGES OF GEOSYNCLINAL DEVELOPMENT OF 'HERCINIAN MASSIFS' OF FRANCE AND SOUTH GERMANY[1]

by

Ye. V. Pavlovskiy

This paper is an attempt at a systematic, but brief analysis of the development of a geosynclinal province including the Armorican and the Central massifs of France, and the Vosges, Schwarzwald, and Odenwald. This province was already in existence in late Precambrian time and developed until the end of the Paleozoic.

This author had the opportunity to become personally acquainted with some of these massifs [4, 5], which has induced him to consider a number of problems of long standing in the tectonics of West European Hercinian rocks, and to attempt to shed new light on them.

The initial stage of this geosynclinal development, accessible to observation within this part of Western Europe, occurred at the close of the Precambrian, in a period which many students call the Brioverian and Infra-Cambrian, in France; the Algonquian or Late Algonquian, in Germany; and Rhiphean, Sinian, upper Proterozoic, and late Precambrian, in the Soviet Union.

## A. LATE PRECAMBRIAN GEOSYNCLINAL PROVINCE. THE ROLE AND SIGNIFICANCE OF CADOMIAN (ASSINTIAN, EARLY BAYKALIAN) FOLDING

### I. Armorican Massif

On the basis of P. Pruvost's study [32], it is possible to differentiate the following structural elements of Armorica: Ligeria, occupying all of south Brittany, including the Vendée; the "Armorican Trench", narrow in the west in the Douarnenez Bay area, and broadening in the east where its northern and southern boundaries pass through Laval and Angers, respectively; Domnonea, along the north coast of Brittany, from Brest to St. Malo; and Mancellia and Normania which, like Domnonea, are located north of the "trench" area and form the northeastern and northern parts of the Armorican massif (Figure 1).

1. The "Armorican Trench", a segment of the northern hercinid branch, has all the features of a typical geosynclinal trough, initiated in Precambrian time. Its sedimentation proceeded uninterruptedly, beginning with the Precambrian (Brioverian) and continuing through the Middle Devonian [32, 36]. Its most strikin structural feature is the two related deep faults which define it in the north and south and which for some reason have not attracted much attention, up to now. These boundary faults undoubtedly are related to deep and long-enduring deformations. Initiated at the close of the Precambrian, they cut off the Armorican Trench from the rest of the vast Brioverian geosyncline affected by an intensive Cadomian (Assintian, Early Baikalian, upper Proterozoic) folding. It looks as though the Armorican Trench of Brittany has dropped out of the general "field of force" of the Cadomian folding.[2] Phenomena of the ancient Brioverian metamorphism and granitization appear to be missing within the trench [32, 36]. The marginal deep faults have strongly affected the trend of Cadomian and Hercinian folding and of subordinate synorogeni granitoid intrusions (both ancient and Hercinian in adjacent areas of Ligeria, Domnonea, Mancellia, and Normania. For a long period of time (from the Cambrian to Dinantian) these faults were the loci of assorted lava flows.

These two main deep faults of the Armorica, initiated in the Brioverian and perhaps even earlier, approach each other in western Brittan and probably merge in the Atlantic coast area. Similar features are displayed by a "cluster" of deep faults in Scotland (Moine, Great Glen, Marginal Rift), also merging in the adjacent part of the Atlantic [3].

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[1]Stadii geosinklinal'nogo razvitiya "Gertsinskikh massivov" frantsii i yuzhnoy germanii. Article dedicated to the memory of Natalia Vasil'yevna Frolova.

[2]It should be kept in mind, however, that, according to E. Bolleli [36], there is a local unconformity between the Cambrian and Brioverian, for example, south of Rennes. The regional significance of that phenomenon is obscure, as yet.

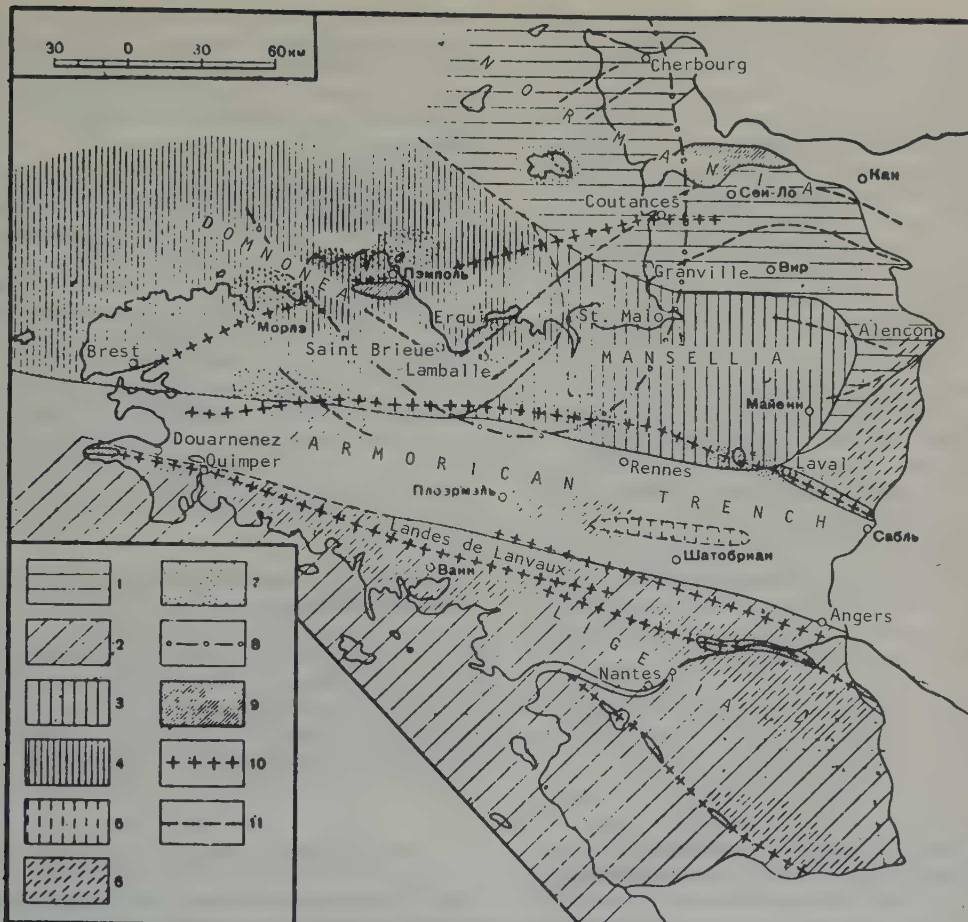


FIGURE 1. Paleogeographic map of the Armorican massif in the Cambrian (and Silurian, after P. Pruvost, [32]).

Areas of uplift, gradually affected after the Cadomian folding by Paleozoic marine transgressions: 1 - Middle Cambrian transgression; 2 - Upper Cambrian transgression; 3 - Arenigian transgression; 4 - Gedinian transgression; 5 - Ben-de-Bretagne swell (Upper Cambrian); 6 - main areas of Cambrian or Ordovician submarine flows; 7 - same for the Dinatian; 8 - boundary of Permian fracture flows; 9 - Permian or Carboniferous continental deposits (following Sudetan folding); 10 - axes of principal anticlines (Sudetan phase); 11 - trend of the Bretonian folds.

The Brioverian section is represented by sandstone and slate interbedded with limestone, and locally alternating with extrusives. Higher up, phthanites appear in beds among terrigenous deposits. This section, whose over-all thickness reaches several kilometers is capped by sandstone, arkose, shale, and conglomerate. French students assign a flysch origin to the entire Brioverian section.

2. Tectonics of the Ligerian province, as designated by P. Pruvost [32] and located south of the Armorican Trench, are characterized by the following features. Ligeria was the province of an intensive Cadomian folding which produced strongly compressed latitudinal and sublatitudinal linear folds. The tightest compression of Cadomian folds is present in an area immediately adjacent to the south marginal fault. Among them is the Lanvaux anticline, studied by A. Fauret-Muret [18]; related to it is the syntectonic Lanvaux "cold" granite which pierces, diapir-like, its contact halo. The degree of compression in Cadomian folds increases also along the trend, from east to west, toward the Douarnenez Bay (the convergence area of the northern and southern marginal faults of Brittany).

The Brioverian section of Ligeria is similar to that observed in the Armorican Trench: arkosic sandstone and shale on top; a phthanitic

horizon in the middle (corelative with the Lamballe horizon of north Brittany); and finally a thick sequence, about 2 km thick, of assorted sandstone, tile slate, and limestone, interbedded with rhyolite, pyroxenite, and eclogite. Quite conspicuous are phenomena of an ancient Brioverian regional metamorphism, affecting the middle and lower parts of the section. There are zones of "upper" and "lower" mica schist, underlain by "basement migmatites" (embrechites and anatectites). The Moelan and Lanvaux intrusions originated in the course of Cadomian folding. Following the Cadomian folding, all of Ligeria was involved in an uplift.

3. The Normania Brioverian, studied recently by M. Graindor [22], is peculiar and differs from the Brioverian both of north and south Brittany. Its main distinction is the presence of two phases of Cadomian folding, which is not true for the rest of Armorica. Another feature is the presence of a tillite sequence in its upper part (the "Granville pudding", [22, 38]). Furthermore, the Normania Brioverian appears to be much thinner than the correlative deposits elsewhere in Armorica, especially in the Central Massif of France.

The lower interval of this section (the Erqui formation) consists of thick (about 1000 m) spilitic keratophyres (banded diorite, meta-spilite, meta-gabbro, meta-basalt, meta-dacite, meta-rhyolite) with subordinate sedimentary rocks (amphibolite and pyroxenite para-hornfels, quartzite, and cordierite schist). The Middle Brioverian (several hundred meters) is made up, as elsewhere in Brittany, of phyliite, quartzite, arkosic sandstone with a phthanitic horizon (radiolarian ?), shale, and graphite schist overlain by extrusives (rhyolite and the St. Germain-de-Gueyar andesite). On the whole, the Middle Brioverian consists of siliceous-volcanic formations.

The Upper Brioverian rests unconformably on various Lower and Middle Brioverian rocks and is made up of Granville tillite overlain by non-metamorphosed shallow-water terrigenous De la Laize deposits. The entire Brioverian section has been assigned a flysch origin, by French students, on the basis of its rhythmic stratification, submarine slumping, cross-bedding, uneven bedding surfaces, and assorted wash and ripple marks.

The two-phase Cadomian folding has produced in Normania, as elsewhere in Armorica, a system of sublatitudinal linear folds. They are strongly compressed, often isoclinal, with a characteristic abrupt undulation of their hinges and the presence of cross folding. The development of syntectonic granite intrusions (of the Atis granite type), elongated with the trend of folding, is related to the second phase of Cadomian folding. Judging from the most recent data [33], a majority of the Normandy granite massifs (with the unquestionable exception of certain minor granite bodies, the Flamanville and Alençon) belong, contrary to earlier concepts, to ancient Precambrian formations and are related, according to all evidence, to the Cadomian folding.

4. Domnonea and Mancellia, which form the northern part of Brittany, display their specific features of development, as do the preceding Armorican structural elements. Recently discovered in the eastern part of Domnomena, in the St. Brieuc Bay, is the crystalline basement resting on which, unconformably and transgressively, is the Lower Brioverian [14]. This "basement complex", named the Pénevrien, is made up of mica schist, amphibolite, migmatite, and granitic gneiss, i.e., rocks which are similar, both in initial constitution and degree of metamorphism, to, perhaps, the lower Brioverian of South Brittany (the Cornouailles anticline).

The northern Brittany Brioverian section is the same as in Normandy, except for the absence of tillite ("Granville pudding"). The trend of Cadomian structures in Domnonea and Mancellia is largely east-northeast, parallel to the north Armorican marginal fault, adjacent to them in the south. It is probable that some of the granite intrusions, as in Normandy, are related to this ancient Cadomian folding.

## II. The Central Massif of France

1. Judging from the data obtained by the Clermont school investigators, an ancient core, mentioned by J. Jung [25], makes up the bulk of the Central Massif. In the north (Marche, North Foraise, Lyonnais, and Morvan), the basement structures have been reworked by the hercinids. According to all evidence, the southwestern and the southern parts of the massif (Bas Limousin, Rouergue, "crystalline Albigeois", Montagnes Noires, and the Cévennes) belong to hercinids and caledonids reworked by Hercinian folding (Figure 2).

This ancient "core" is made up of a thick series (no less than 12 km) of late Precambrian sedimentary and volcanic rocks (Brioverian, Rhiphean). A startling feature of this series is its stratigraphic unity and the lack of appreciable breaks and unconformities, as noted by all students [10, 11, 17, 23-25]. Typical of the western part of the massif (Limousin) is a flysch formation closely interbedded with a spilitic keratophyre and embracing all of the visible thick ancient section (two-cycle flysch). Near the Argentat faunt zone and east of there, the flysch is replaced by a terrigenous, pelitic formation. This suggests that the Argentat zone is an ancient deep fault which originated in the course of development of a Brioverian (late Precambrian, Rhiphean) eugeosyncline.

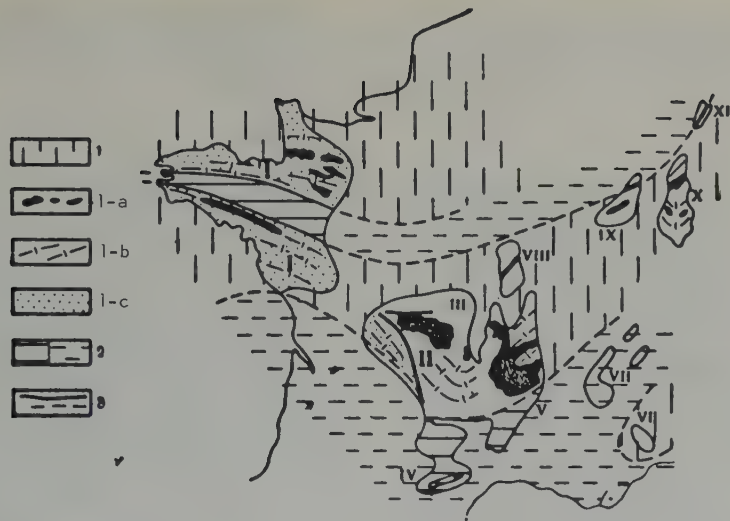


FIGURE 2. Paleotectonic map of the end of the Precambrian (results of Cadomian folding).

1 - zone of the Cadomian folding; 1-a - Cadomian granitoids; 1-b - trend of Cadomian folds; 1-c - area of Cadomian flysch distribution; 2 - provinces not affected by the Cadomian folding; 3 - deep faults. I - Armorica; II - Central Massif of France; III - its northern margin; IV - Montagnes Noires; V - the Cévennes; VI - Mercantour; VII - Belledonne and Grand Paradis; VIII - Morvan; IX - the Vosges; X - Schwarzwald; XI - Odenwald.

This sedimentary-volcanic series is cut by pre- to synorogenic intrusions of gabbro, peridotite, and eclogite. The series has undergone two stages of metamorphism. The first, the Brioverian phase, is expressed by regional tectonic metamorphism which has produced a number of isometamorphic zones (upper and lower gneiss, upper and lower mica schist), with "basement migmatites" (Aubusson gneiss) at the bottom.

The close of the Brioverian was marked by a folding paroxysm (Cadomian, Assintian, early Baykalian) which produced a complex system of strongly compressed linear folds complicated by thrusts. A combination of "Armorican" and "Variscan" ancient structural trends in the Central Massif (arcuate, convex to the south) was probably formed during the Cadomian folding. The origin of large post-orogenic (?) anatectite granite bodies of Guéret, Foraise, and Velet was related to that folding.

2. The northern margin of the Central Massif (Marche — north of Auvergne — Morvan). The crystalline basement here is similar in constitution and structure to the Brioverian "core" of the Central Massif. The magnitude of the erosional truncation in Cadomian folded structures is estimated by J. Jung [23-25] to be very large (up to 20 km). Unlike the "core", the basement rocks have undergone three rather than two stages of regional metamorphism. The last one was a Hercinian stage of retrograde metamorphism [10, 31].

3. The southern margin of the Central Massif (southwest Limousin — Rouergue — Montagnes Noires — South Cévennes). The southern margin of the hercinids is marked by the presence of a full and thick Paleozoic section, conformable (except for the axial part of the Montagnes Noires) with the Precambrian; it is also marked by the absence of ancient metamorphism (Brioverian) and of Cadomian folding. The Brioverian is usually represented by shale and arkose interbedded with limestone, a terrigenous formation of the miogeosynclinal type, not typical of other parts of France.

## III. The Vosges

As shown by J. Jung [25, 30], the Vosges province is broken up into two uneven parts by the major sublatitudinal Laley-Lubine fault: the smaller northern and the larger southern parts. Resting at the base of the section, in the south, is an ancient metamorphic series of biotite and sillimanite ("lower") gneisses with beds of amphibolite and cipolino marble, and migmatites. This series is correlative with the lower part of the Brioverian "core" of the Central Massif. Latitudinal trends of the basement

folding are typical of this area. The biotite granite (Verrery) appears to be related to the Cadomian folding (see Figure 2).

### IV. Schwarzwald

Belonging to the late Precambrian (Algonquian, Brioverian) of the Schwarzwald is a series originally consisting of graywacke, arkose, and shale with thin marl beds and less common carbonaceous and carbonate rocks [28, 39]. A rapid alternation of coarse- and fine-grained deposits is typical of this area, with locally preserved traces of cross-stratification. Argillaceous components predominate in the extreme south of the Schwarzwald. North of a nearly longitudinal zone of deep faulting, extending from Badenweiler in the west to Lenzkirche in the east, coarser terrigenous sediments are prominent in the Algonquin section. These facies changes are reminiscent of the Limousin Brioverian where the old Argentat fault appears to have determined the development of various structural facies zones of the Brioverian geosyncline, in the Central Massif province, and defined the Limousin flysch trough in the north and northeast. It is possible that in the Schwarzwald, too, the deep fault zone, quite definite at the close of the Devonian and the beginning of the Carboniferous, had already existed at the close of the Precambrian, in the Algonquian.

The Precambrian sedimentary section of the Schwarzwald underwent an intensive regional metamorphism (development of paragneiss, anatectites) and was gathered into a system of linear folds (Assintian folding), arcuate and smoothly changing their trend from latitudinal to a northeasterly, at the eastern margin of the massif. Palingenetic granites (anatectites), turned to orthogneiss, are a typical element of the Schwarzwald "basement complex". Of a subordinate nature are anorthosite and basic and ultrabasic rocks; the igneous origin of some of them has often been questioned.

In texture, structure, and mineral composition, Algonquian paragneisses of the Schwarzwald correspond to "lower" gneisses of the Central Massif, while the para-anatectites correspond to the "basement migmatites".

On the whole, the entire basement complex of the Schwarzwald correlates well with the Vosges basement.

The role of Precambrian formations in the Odenwald is less clear. The Odenwald is known to consist of two unequal parts separated by the major Otzberg fault zone, trending north-northeast. East of that fault (Bollstein), hornblende gneiss forms the core of a large, submeridionally trending anticline, with its northwestern limb cut off by the Otzberg fault. Metamorphic schist is developed on either side of the gneiss anticline. Most students [36, 37] assign both the gneiss and schist to the Hercinian basement rocks.

Developed in the western part of the Odenwald is a series of pararocks, virtually missing in the south of the Vosges and in the Schwarzwald. These are assorted varieties of pararocks, metamorphosed largely under epizone and mesozone conditions. In addition, there are quartz-biotite and graphite schist, graphitic quartzite, para-amphibolite, kinzigaite, and plagioclase-cordierite and corundum-cordierite schists. This series is quite thick. Judging from the presence of metamorphosed volcanic tuffs and large basic intrusions (gabbros), it was formed under eugeosynclinal conditions. G. Klemm [36] assigned it to the Paleozoic but E. Tröger [37] believes it more probable that its lower part belongs to the Algonquian, and the upper, to the lower (?) Paleozoic. In the light of these concepts, it is possible that the entire Bergstrasse Odenwald, like the northern part of the Vosges, belongs among structures related to the Armorican Trench (Figure 2).

## B. THE GEOSYNCLINAL PROVINCE OF THE LOWER PALEOZOIC (CALEDONIAN STAGE)

### I. Armorican Massif

1. The Armorican Trench. Resting conformably on Brioverian deposits is a eugeosynclinal Cambrian section (1 to 1.5 km thick) of conglomerate, arkose, green schist, and limestone lenses. Extrusives appear in the upper part of the section (including andesite and rhyolite). The Ordovician (1250 to 2000 m) is made up of red conglomerate, sandstone, and shale, interbedded with extrusives (dolerite); higher up there are Arenigian "Armorican" sandstones overlain by the Angers tile slates (Llandeilian), with a bed of oölitic iron ore at the base. Caradocian sandstone with shale and occasional limestone beds locally contain a considerable amount of volcanic tuff. The Gotlandian (about 500 m thick) is made up of sandstone and black carbonaceous shale. Overlying them conformably are Devonian and Carboniferous deposits. The Brioverian eugeosynclinal regimen persisted in the early Paleozoic and later on, in the Devonian and Dinantian.

Caledonian movements were local and of low intensity. A latitudinal swell, Ben-de-Bretagne, originated in the eastern part of the trench, at the close of the Cambrian ([32]; Figure 1).

2. Ligeria. The uplift which followed the post-Cadomian folding became a subsidence at the end of the Cambrian; this subsidence proceeded unevenly and at a different rate. New fault trends originated in the northeastern part

of Ligeria (the Ancenis "basin"), parallel to the main southern fault. This marginal zone was the site of geosynclinal sedimentation which began in the Late Cambrian and was similar on the whole to that of the Armorican Trench.

In the remaining and larger part of Ligeria, particularly in the Vendée, the lower Paleozoic section was greatly reduced, represented by Upper Cambrian, Tremadocian, and Arenigian (red sandstone and shale, rhyolite, arkose, and conglomerate). The lower paleozoic rests transgressively and unconformably on the Brioverian and is separated by an unconformity from overlying Middle Devonian (Givetian) limestone. P. Pruvost [32] believes that a swell-like anticlinal structure, Landes de Lanvaux, extended along the southern marginal fault, having originated at the Gotlandian-Devonian boundary.

3. The uplifts which affected Normania after the Cadomian folding were short-lived. As early as the Middle Cambrian, all of Normania was affected by a marine transgression. The section begins here with conglomerates changing upward to green meta-shales and limestones. The Tremadocian and Upper Cambrian, unlike their correlatives in the Vendée, are free of extrusives and are represented by motley sandstones and shales. The remaining and largest part of the Ordovician and Gotlandian, too, is represented by terrigenous rocks. The miogeosynclinal marine conditions, developing since the Middle Cambrian, continued into the Devonian when sediments were deposited conformably on the Gotlandian. There is no evidence of Caledonian folding.

4. The epoch of post-Cadomian uplifts was quite long in Domnonea and Mancellia. The latter was submerged only in Arenigian time, with Domnonea following it at the beginning of the Devonian. Mancellia and particularly Domnonea were positive geanticlinal elements in the structure of the lower Paleozoic geosynclinal province; as such, they constituted the source areas for clastic material in the adjacent troughs, the Armorican Trench eugeosyncline and the Normania miogesyncline.

## II. The Central Massif

1. The ancient core of the Central Massif, like its northern margin (Marche, the northern part of Auvergne, Morvan) entered a long and stable geanticlinal stage, following the completion of the Cadomian folding. Only its northern margin was involved with Domnonea, in the Devonian and Dinantian, in a new and brief stage of geosynclinal development. In the "ancient core" area, the geanticlinal conditions persisted till the end of the Paleozoic. There are no traces here of any lower Paleozoic sedimentation (Figure 3). We shall not pause for the M. Chenevoy argument [11] for the presence of a Cambrian and Silurian bed" in the upper part of the metamorphic "core" of the Central Massif. This interesting topic is dealt with in another work [5].

From all evidence, the formation of a large Central Massif geosyncline in the very beginning of the Paleozoic strongly affected the further development of the West European geosynclinal province. Instead of the immense and somewhat vague, Brioverian geosyncline, at the opening of the Paleozoic a distinct splitting of the geosyncline into northern and southern branches separated by the Central Massif geanticline occurred. The paths of Paleozoic development for these branches were far from siliar.

The Vendée, with its reduced Paleozoic section, probably constituted the northwestern periclinal part of the Central Massif geanticline. In the northeast, this geanticline undoubtedly included the south Vosges, Schwarzwald, probably east Odenwald (Bollstein), and possibly the Czech crystalline massif.

In other words, there are no reasons to relate the origin of the Moldanubian block, as a positive structure of the geanticlinal type, to some very ancient Precambrian crustal movements. The data on hand quite reliably tie the Moldanubicum's origin to the beginning of the Paleozoic. Brilliant geologic and petrographic studies of the Clermont school [10, 11, 17, 23-27, 31, 34] have provided means for an understanding of those processes taking place in the geanticlines during the Paleozoic. The Brioverian metamorphic series, having undergone a Cadomian folding and a stage of the ancient Brioverian regional metamorphism, went through a second stage of metamorphism, in the early Paleozoic.

This second (pre-Late Devonian) metamorphic stage was expressed by a paragenesis of mica and tourmaline in various zones of ancient metamorphism, as well as by "stratoid migmatites" (potassium metasomatism) and metasomatically "oriented" diorite. This metamorphic stage is close in time to the second epoch of tectonic movements resulting in "arcs", i. e., folds with a large radius of curvature and apparently expressing the reaction of the ancient "core" to Caledonian folding in the southern Paleozoic geosynclinal province (Montagnes Noires, south Cévennes, etc.). No intrusions, including the granitoid, corresponding to this second (Caledonian) development stage, have been observed within the "core".

2. The south branch of the Paleozoic geosynclinal province. The transgressive lower Paleozoic series appears to rest conformably on Precambrian (Brioverian) formations [19, 20], with only local sedimentary breaks (Soresoix, East Lacon, Lodevoix). The onset

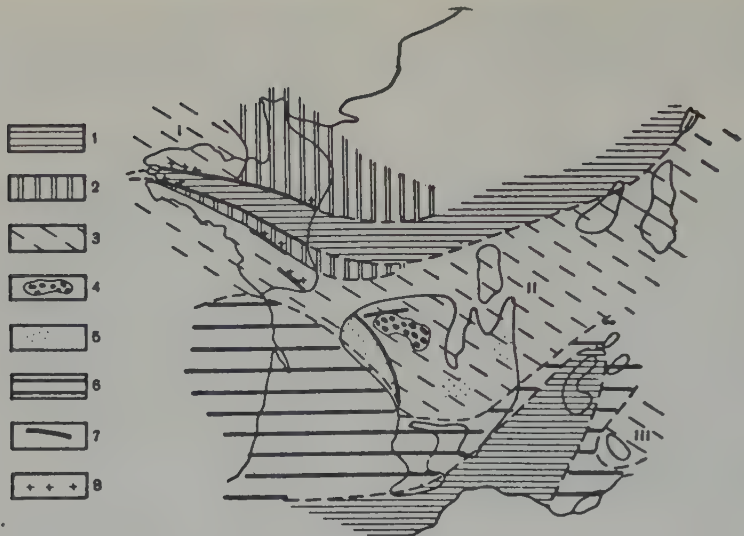


FIGURE 3. Paleotectonic map of the Lower Paleozoic

1 - uninterrupted sedimentation zones inherited from the Brioverian; 2 - segments of the Cadomian folded zone, reinvolved in a early Paleozoic geosynclinal sedimentation; 3 - geanticlinal zones formed at the beginning of the Paleozoic: I - Domnonea; II - main geanticline — the Moldanubicum; III - Mercantour; 4 - the Guéret revived granite massif; 5 - provinces of Caledonian migmatization and metasomatism; (2nd stage of Brioverian metamorphism in the Central Massif); 6 - zone of Caledonian (Taconian) folding; 7 - deep faults; 8 - submarine flows.

of the Cambrian is connected with a distinct transgression, from south to north and overrunning the south slope of the Central Massif geanticline. Terrestrial volcanism preceded the Cambrian transgression [9, 19, 34].

Also in the Precambrian, the Mandic granite massif was formed in the axial zone of the Montagnes Noires; it was related to weak local manifestations of the Cadomian folding. The Cambrian section begins with the middle part of its lower division, represented by Macrori conglomerate and arkosic sandstone overlain by archaeocyathid limestones. The middle division is made up of calcareous, arenaceous and other shales with Paradoxides (maximum Cambrian transgression), overlain by areno-argillaceous Upper Cambrian deposits. The Central Massif geanticline appears to have been the source of clastic material (Figure 3).

A facies analysis by B. Géze [19, 20] suggests that, in the Cambrian, the axial part of the Montagnes Noires was either land or a shallow zone. The sedimentary section is thinner, here (500 to 1000 m) and clastic material is coarser. The thickest Cambrian sections (up to 3000 m thick) are associated with two troughs (the northern and the southern) separated by a sublatitudinal uplift of the axial zone. By its lithologic features, this Cambrian section is of a miogeosynclinal type. The miogeosynclinal regimen was inherited here from the preceding Brioverian type, as mentioned before, and persisted for quite a long time during the entire early Paleozoic.

In many places, the Ordovician is separated from the Upper Cambrian by a break (with the Lower Trenadocian missing) and rests unconformably on various Cambrian horizons. B. Géze believes that the Cambrian-Ordovician boundary is marked by a regression and weak folding, with subsequent erosion. Ordovician areno-argillaceous deposits are lithologically similar to those of the Upper Cambrian. Coarser clastic material increases in prominence at the beginning of Middle Arenigian. The minimum thickness of the Tremadoc-Arenigian formation has been estimated at 1000 to 1500 m. The absence of the Upper Arenigian and all of the Llandeillian is related to a distinct manifestation of Taconian folding resulting in a series of sublatitudinal linear folds, slightly overturned to the north, toward the Central Massif geanticline. As pointed out by B. Géze, the Taconian folding was considerably more intensive than formerly believed. "It is only slightly less intensive than in the Ardennes." Taconian structures are especially well expressed in the Minervoix Mountains (southwes of the south slope of the Montagnes Noires).

A new major transgression developed in Caradocian time; it proceeded from the south, as before, and advanced northward, into the province of eroded Taconian folds. Conglomerate and coarse sandstone with a ferruginous cement, in the lower part of the Caradocian section, consist of the fragments of all underlying ancient rocks, including the Precambrian. Deposited near the Montagnes Noires axial uplift, in Late Caradocian, were areno-argillaceous sediments, with limestone beds in the south. The Gotlandian is conformable, represented by calcareous shale which changes in deeper reaches of the troughs to fine-grained black shale with pyrite and rare limestone intercalations. A distinctive horizon of ferruginous oölites rests at the base of the Gotlandian. The Gotlandian section is usually incomplete, with the upper part of the Ludlow and all of the Dawton missing, which suggests uplifts and "a local posthumous Caledonian pulsation (Ardennes phase)".

The Caradocian-Gotlandian section on the south slope of the Montagnes Noires amounts only to 200 m; it is even thinner on the north slope. It appears, then, that in the course of Caledonian orogeny, the north slope of the Montagnes Noires, along with the South Cévennes, Albi, and Rouergue, gradually emerged from the sea. It was as if these provinces enlarged the south limb of the Central Massif geanticline which continued to grow during the early Paleozoic. Devonian deposits, as we shall see, are missing in the north slope of the Montagnes Noires and are quite limited in distribution in the South Cévennes (the Vigan thrust area).

It follows from what has been said that a miogeosynclinal regimen, established as early as the Precambrian in the southern part of the Central Massif, persisted there, unabated, throughout the early Paleozoic. According to M. Roques [10], the single-stage migmatization process in the Montagnes Noires region ran its course in pre-Devonian time and probably was connected with the Caledonian cycle. It is of interest that, in its chemistry, the pre-Devonian migmatization is similar to "stratoid" migmatites (second stage of metamorphism) developed in the Central Massif geanticline.

III. The Vosges, Schwarzwald, and Odenwald

Geanticlinal conditions appear to have prevailed here in the early Paleozoic, so that no sedimentation took place. The presence of lower Paleozoic geosynclinal deposits (the Villier and Steige shales) can be assumed, as we have mentioned, only in the northern part of the "crystalline Vosges", north of the Laley-Lubine fault. A similar assumption can be made for the western part of the Odenwald (Bergstrasse). If this is true, a geosynclinal trough should have existed in the northern part of the Vosges and in the Bergstrasse Odenwald, in the early Paleozoic; it was separated from the geanticlinal zone by a fault in the south (the Vosges) and east (Odenwald), in the same way as the Armorican Trench is separated from Ligeria. Seen in this way, the Vosges and Bergstrasse Odenwald can be regarded as an eastern continuation of the Armorican Trench zone which is a component of the northern branch of a Paleozoic geosynclinal province (Figure 3).

## C. THE HERCINIAN STAGE OF DEVELOPMENT OF THE GEOSYNCLINAL PROVINCE

I. The Armorican Massif (Figures 1 and 4)

1. The Armorican Trench. Resting conformably on the Gotlandian is another thick (over 2 km) eugeosynclinal series, an almost complete Devonian section (the presence of the Middle Devonian Givetian stage has not been demonstrated, faunally) represented largely by assorted shales (locally bituminous or calcareous) with subordinate beds and lenses of limestone, quartzite, sandstone, and graywacke. Basic extrusives (dolerites) are present in upper horizons of the Lower Devonian [8, 32]. The Devonian is developed mostly along the northern margin of the Armorican Trench (the Chateaulin-Laval syncline). The Dinantian, represented by a Kulm facies, and attaining locally 1.5 km in thickness (Finistère), rests transgressively on various divisions of the Devonian, on other parts of the lower Paleozoic, or directly on the Brioverian. The Dinantian is made up of conglomerate, sandstone, graywacke, and shale with plant remains. Limestone is commonly conspicuous in the upper part of the section (Viséan). Acid and basic extrusives are associated chiefly with the Tournaisian.

Preserved locally in minor synclines extending along the fault zones are coal-bearing Namurian and Stefanian deposits, separated from one another and from the underlying rocks by a break and a sharp angular unconformity. Permian deposits are missing in the Trench area.

Critical in the folding of the Armorican Trench province were the early Hercinian stages, the Bretagne and Sudeten phases which brought about a system of linear folded structures subordinate to the trend of the Trench. The largest folded forms, compressed and complicated by faults, trend west-northwest to east-southeast. These are the Rennes anticlinorium and the vast Segre synclinorium which merges in the south with the St. Julien de Vouvant synclinorium.

Hercinian granite intrusions, with granulites

widely distributed among them, are concentrated mostly in the western part of the Trench, where the northern and the southern marginal faults come together. A particularly large "granulite" field extends along the southern fault, graphically demonstrating its spatial and probable genetic connection with the latter.

Narrow and very long synclines of the Sudetan folding, such as the Chateaulin-Laval and Quimper-St. Julien de Vouvant, extending for 250 to 300 km and shown on the map as narrow bands are striking in their peculiar morphology. These features are especially conspicuous on G. Goguel's structural map of France. Their strict association with zones of marginal faults cannot be accidental; it probably is evidence of a genetic relationship.

The eugeosynclinal conditions of a comparatively quiescent sedimentation in the Armorican Trench province traceable from the Brioverian to the end of the Devonian, was interrupted for a short time by the Bretagne folding; it resumed in the Dinantian, but not for long. The sudetan folding was of a terminal nature. As in the Central Massif, Namurian and Stefanian coal measures were deposited in zones of active faults. They can be regarded as molasse-type deposits, involved in a "posthumous" folding.

Permian deposits are missing within the visible portion of the Trench, as are the Mesozoic. The platform mantle is represented by locally developed Tertiary marine and genetically diversified Quaternary deposits.

2. In the northeastern part of Ligeria, near the southern marginal fault (the Ancenis "basin"), a continuation of geosynclinal sedimentation occurred in the Devonian. This sedimentation had been initiated in the Late Cambrian and was similar to that taking place in the Armorican Trench. However, in contrast to the Trench area, the Gedinnian, Siegenian, and Eifelian Devonian stages are missing in the Ancenis basin. Nor is there any break between the Upper Devonian and the overlying Lower Carboniferous. Continental deposits, conglomerate and graywacke with plant remains, appear in an upper (Viséan) part of the Kulm. Namurian coal measures rest with sharp unconformity on older formations. Westphalian, Stefanian, and Permian deposits are missing.

In the remaining larger part of Ligeria, particularly in the Vendée, the Paleozoic history was quite different. As noted before, the entire Paleozoic section is much shorter, here. Resting transgressively on Upper Cambrian and Lower Ordovician red sandstone, shale, and extrusives are Givetian limestones, the only Devonian representative. The upper part of the Paleozoic section is made up of a coal-bearing series (Namurian, Westphalian, and Stefanian), unconformable on the underlying rocks. There also are Namurian-Westphalian and Westphalian-Stefanian angular unconformities.

A system of linear Hercinian structures, shaped during a long period and in several stages (Bretagne, Sudetan, Erzgebirge, and Asturian phases), is subordinate to a single Armorican trend. Simultaneously, the axes of Hercinian folds are subparallel or parallel to the trend of the southern Armorican deep fault. As is true for the entire Armorica, a cluster of Ligerian folds is strongly compressed in the extreme west, where the two main deep faults of Brittany come together. This phenomenon was noted long ago by Ch. Barroy [8, 21, 36].

Associated with initial phases of the hercinid: are a new stage of regional metamorphism and migmatization. "Augen" embrechite, anatectite morbianite, and embrechite with fibrolite, cordierite and local garnets originated in the Cornouaille anticline area, as a new formation in previously metamorphosed Brioverian rocks. The migmatization front shifted upward, toward the base of upper mica schist.

This process of regional metamorphism developed simultaneously with a rebuilding and "twisting" of the Cadomian Cornouaille anticline which had changed its former longitudinal trend somewhat to a northwesterly, Armorican one. The migmatites are cut by "late migmatite" granite intrusions (Guidel, Carnac). The Sudetan folding developed under conditions of rising mountain chains. Connected with this phase is the final shaping of Hercinian folded structures, throughout Brittany, as well as the intrusion of a sizable number of granite bodies. Namurian through Stefanian molasse coal-bearing series were deposited in isolated depressions within a new mountain structure; they coincided with lines of deep faults, partly originating as early as the Brioverian and partly in the Paleozoic. At the close of the Namurian (Erzgebirge folding) and of the Westphalian (Asturian folding), the coal measures were folded along the same Armorican trend. The bulk of dimicaceous granite intrusions (granulite) is associated with these terminal phases of a long Hercinian orogeny. The connection with fault zones if particularly conspicuous in the Stefanian where the "coal furrows" were formed. At the onset of the Permian, the entire Ligerian province became part of the uplifted epi-Hercinian platform almost devoid of a sedimentary mantle.

Ligeria, especially its Vendée sector, can be regarded as a northwesterly periclinal termination of the main Central Massif geanticline reworked partly by Caledonian but mostly by Hercinian movements.

3. Normania. The miogeosynclinal marine conditions inherited from the lower Paleozoic

persisted till the middle of the Devonian (including the Eifelian). Givetian deposits, as well as the Upper Devonian, are missing. The Bretagne folding had created a system of folds with arcuate axes convex to the north. The eroded, early Hercinian folded complex is overlain transgressively by Tournaisian red conglomerate, sandstone, and shale, also Viséan limestone, deposited in interior basins of a newly-created mountain system. As in the underlying miogeosynclinal Paleozoic, extrusives are missing in the Dinantian. The Sudetan folding in Normania (unlike that in the Ligerian Trench areas) apparently was merely local (e. g., the Coutances syncline).

Stefanian coal measures (Littrie) are conformable with the overlying Permian terrigenous clastic sediments and are essentially part of a lower interval of the epi-Hercinian platform, affected by the Saal movements.

Thus, Normania is a province with a reduced Brioverian section, which underwent a two-phase folding accompanied by numerous syntectonic granite intrusions. In the Paleozoic, it was a miogeosynclinal type province. Later on, Normania was most affected by the Bretagne movements associated with which were a few minor granite intrusions. A waning of the geosyncline and the formation of a mantle for the epi-Hercinian platform was initiated here earlier than in other Hercinian massifs: at the close of the Carboniferous.

4. Domnonea and Mancellia. A period of post-Cadomian uplifts, which affected all of Armorica except for the Trench, was especially long in Domnonea and Mancellia. The latter was submerged as late as the Arenigian, while Domnonea persisted into the Early Devonian. Marine conditions lasted here only until the Middle Devonian. Terrigenous deposits predominate, with the Coblenz limestone known only from the Mancellia region. In Domnonea, basal Lower Devonian beds (Gedinnian shale and the Plougastel quartzite) rest directly on greatly disturbed Brioverian shale. In Mancellia, similar relationships have been observed between the Brioverian and the Arenigian "Armorican" sandstones. According to P. Pruvost [32] a Bretagne folding was responsible here for the St. Brieuc anticline, with its arcuate axis convex to the south. The prevailing trend of the Domnonea Bretagne folds is to the northwest.

In the Dinantian, mass flows of porphyrite took place in the zone of the north Trench fault, along the southern margin of Domnonea and Mancellia. A new Brest-Paimpol fault zone originated in the center of Domnonea, with assorted volcanic products (porphyrite, orthophyre, dolerite, volcanic breccia, and tuff) ejected on the surface, and along it. In addition to volcanic rocks, the Dinatian is represented by conglomerate, shale, calcareous shale, siliceous rocks and less common limestone lenses. The Dinantian has been metamorphosed at the Hercinian granite contact; because of that, it took a long time to distinguish it from the Brioverian.

The Sudetan folding had a northeasterly trend. The axis of the largest syncline, extending from Brest to Coutances in Normandy, coincides with a newly formed Dinantian deep fault. Assorted granite intrusions (including granulite) accompanied the long Hercinian orogeny. Some of them were undoubtedly connected with the Bretagne folding, while some others were associated with the Sudetan. Unlike Normania, the areas of Domnonea and Mancellia were the site of a mass intrusion of Hercinian granitoids.

Namurian, Westphalian, and Permian continental red molasse (conglomerate, quartzite, arkose, and shale), which accumulated in isolated depressions within a newly-formed Hercinian chain,[3] were compressed by "posthumous" movements (the Erzgebirge, Asturian, and Saal phases of folding). Porphyrite flows occurred in Domnonea, in the Permian.

In a post-Permian time, a considerable part of Domnonea, as well as the western margin of Mancellia and Normania, became a site of mass fissure flows of porphyrite and dolerite. Dikes of these rocks commonly have a meridional trend. The lavas flowed over an already peneplaned province. Their effect is associated with early stages of mantle development over the epi-Hercinian platform.

On the whole, the development of tectonic structures in Domnonea is most reminiscent of the northern part of the Central Massif of France, in the south of the Vosges, and in the Schwarzwald. "Ancient cores" were involved here, in the Devonian and Dinantian, in a new and short-lived stage of geosynclinal development related to the collapse of an ancient cystalline basement and to a revival of movement in zones of ancient deep faults as well as to the origin of new faults.

## II. The Central Massif of France

1. The geanticlinal zone. As noted before, the ancient "core" became, in the early Paleozoic, a geanticline separating the southern Paleozoic geosynclinal province (Montagnes Noires, Rouergue, South Cévennes) from the northern, which is buried to a considerable extent under a Mesozoic-Cenozoic mantle of the Paris basin (synecleases; Figures 2, 3, and 4).

[3]Unlike other Hercinian massifs, Late Carboniferous coal measures are missing here.

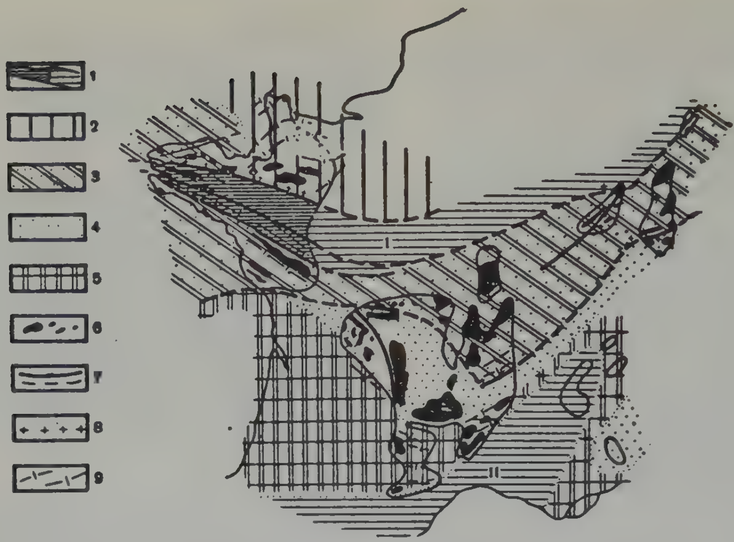


FIGURE 4. Paleotectonic map of the Devonian and Dinantian

1 - Hercinian folding in zones of uninterrupted geosynclinal sedimentation, from the Brioverian through the Dinantian; 2 - Hercinids in the "secondary" geosyncline of Normania and Mancellia; 3 - Hercinian folding in zones of collapse (Moldanubicum and Domnonea); 4 - geanticlinal zone not affected by the Hercinian folding; 5 - Caledonids reworked by the Hercinian folding; 6 - intrusions of Hercinian granitoids; 7 - deep faults; 8 - assorted Devonian-Dinantian extrusives; 9 - trends of the Brittany and Sudeten folds; I - northern branch of hercinids; II - southern branch of hercinids.

The reaction of the Central Massif geanticline to earlier stages of the Hercinian orogeny (Bretagne and Sudetan phases ?) was expressed first of all in the formation of a system of latitudinal, west-northwest trending, and submeridional faults, especially distinct in the west (Limousin); also in a rejuvenation of the ancient Argentat fault zone. The latter, together with some newly-formed Hercinian faults (Usille, Marche), determined the development of some large Hercinian granitoid massifs, with the Bram and particularly the Millevache the most important. A vast body of Marjeride Hercinian granite, in the southern part of the Central Massif, appears to have no connection with the faults. The most typical representatives of Hercinian granitoids are the so-called granulites (dimicaceous granite). Relatively narrow zones of contact haloes have originated along the periphery of granite intrusions [8, 11, 17, 23, 26, 27].

Later Hercinian movements were reflected in the geanticlinal structure as new submeridional faults. The largest of them is the "Grand sillon houiller" which cuts the Central Massif geanticline into almost equal halves. Related to the same tectonic stage is the origin of individual troughs superimposed on the geanticlinal body, with the Ste. Etienne, in the eastern part of the Massif, the largest among them; also in a revival of movement in zones of all older faults.

In individual troughs and fault zones (the "scar" and "suture" troughs),[4] the Upper Carboniferous (Stefanian) witnessed the accumulation of a fresh-water coal-bearing series, up to 3.5 km thick (Ste. Étienne). The trend of these trough and synclinal folds was determined either by faults or by the trend of ancient Cadomian structures, or else independently of the basement structural trend (Figure 5). Stefanian deposits are non-metamorphosed, folded, and cut by normal and reverse faults (the Saal phase of the hercinids). The Saal folding does not appear to have resulted in a linear system; rather it was expressed locally in graben-like fault zones or in isolated synclinal downwarps of the Ste. Étienne basin. As a rule, it is not associated with any evidence of igneous activity. This is a reaction of isolated weakened geanticlinal zones to terminal stages of Hercinian folding, in the adjacent geosynclinal provinces. Stefanian coal

[4] The fortunate terms, "scar" and "suture", introduced to Soviet literature by A.I. Suvorov and N.P. Kheraskov, were applied by them to anticlinal structures. Here, on the other hand, we deal with synclines, very widely developed in Hercinian massifs of France and south Germany.

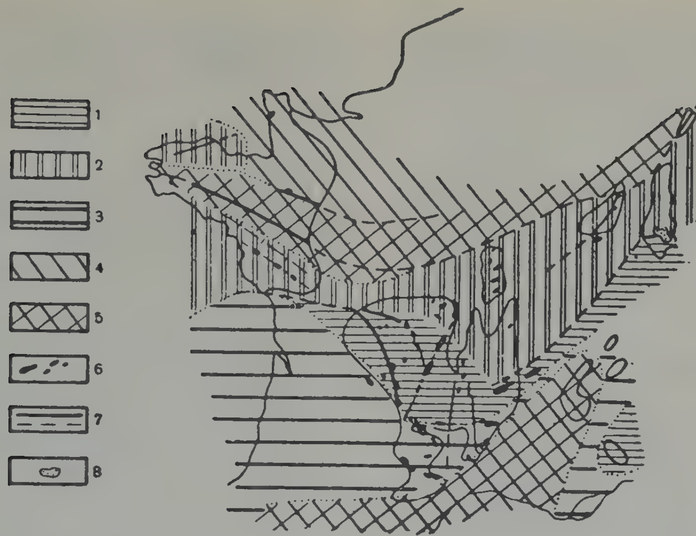

FIGURE 5. Paleotectonic map for the end of the Carboniferous (Stefanian)

1 - geanticlinal zone not affected by Hercinian folding; 2 - foundering zones of geanticlines affected by the Bretagne and Sudeten foldings; 3 - Caledonids reworked by early-Hercinian folding; 4 - Hercinian folding in the "secondary" geosyncline of Normania and Mancellia; 5 - early Hercinian folding in provinces of prolonged geosynclinal sedimentation (Brioverian-Dinantian); 6 - superimposed and "scar" downwarps filled with coal-bearing and other Stefanian molasse; 7 - ancient and newly-formed fault zones; 8 - Upper Carboniferous dimicaceous granite of the Schwarzwald.

measures can be assigned to the molasse-type formations ("interior" molasse of geanticlinal zones).

It appears from what has been said that the effect of Caledonian and Hercinian movements on ancient linear Cadomian structures, within the Central Massif "core", was comparatively small.

The subsequent history of that "core" is, in effect, a loss of its geanticlinal aspect, beginning with the Permian, in connection with a cessation of geosynclinal conditions throughout the Hercinian of Western Europe. In the structure of the epi-Hercinian platform, the "core" plays the same part as do the shields of more ancient platforms, the Russian, Siberian, North American, etc. The persistent tendency toward uplift, first clearly discernible at the opening of the Paleozoic, is still there. As in ancient shields of east Africa and east Siberia, the reaction of the Central Massif of France to Alpine movements was expressed, at the close of the Eocene and especially in the Oligocene, in the formation of immense troughs (Limagne, Foraise, and other smaller ones) of a "Baykal type" [2], extended meridionally and subparallel to the Alpine orogenic front. These troughs were the sites of active accumulation of lagunal and continental deposits, over one km thick. This process has lasted for a long time and, in fact, is still going on. The originally simple synclinal structure of these troughs was complicated at the close of the Oligocene and in the Miocene, by marginal normal faults with large throws. Their zones were vents for magmatic melts. Multistage flows of assorted lavas from these fractures, lasting from the end of the Oligocene through the Quaternary, have created numerous volcanic "massifs" and "chains", including the famous chain of Quaternary volcanoes crowned by Puy-de-Dome.

2. <u>The northern margin of the Central Massif</u> (Marche — northern Auvergne — Morvan) is a northern branch of the hercinids. A deeply-eroded crystalline foundation, similar in composition and structure to the Central Massif "core" metamorphic series, is transgressively and unconformably overlain by a Devonian-Dinantian thick sedimentary volcanic sequence. The Devonian and Dinantian, preserved in synclines, are gathered into linear folds of the Armorican (northern Auvergne) and Variscan (northeast) trends, especially well expressed in Morvan and Bourbonnais.

The southern boundary of the Devonian-Dinantian is defined largely by major faults (Figure 4). The basement rocks, unlike those of the Central Massif "core", underwent a third stage of regional (retrograde) metamorphism. Fossiliferous Upper Devonian (Frasnian and Famennian), Tournaisian, and Viséan are concordant, forming a single transgressive series. In the southern Morvan and in the Allier River area, the Upper Devonian is made up of limestone and shale overlain by conglomerate and sandstone with plant remains and by shale with limestone lenses, all belonging to the Tournaisian and Viséan [29]. Prominent in the Tournaisian section are andesite and tuff. The Dinantian section is correlative with the German Kulm "facies". In the Brevennes River basin, according to J. Peterlongo [10, 31], the Upper Devonian and Dinantian are represented by a thick series of sedimentary and volcanic rocks (spilite-keratophyre formation) with sills and laccoliths of serpentinite, norite, gabbro, diorite, and alkalic granite. This series is most intensively metamorphosed near the Brevennes marginal fault (under meso- and epizone conditions). The intensity of metamorphism is lower to the north. An involvement of the north limb of the main Central Massif anticline in a brief but tempestuous eugeosynclinal regimen (Late Devonian-Dinantian) appears to have been related to a subsidence (Umbruch)[5] of that zone (Boussac, Marche, Brevennes faults, etc.). Typical of the entire subsiding zone are intrusions of Hercinian "granulite" (dimacaceous granite), widely developed also in the Central Massif ancient "core".

In addition to linear folded structures, the Hercinian orogeny produced a number of major thrusts, with the largest of them apparently located in the Egurand plateau and in the Sioule area [8, 15, 16, 23]. The pre-Stefanian thrusts developed from north to south, i. e., from the interior of a northern branch of the Paleozoic geosynclinal province (buried beneath the Paris Basin sedimentary mantle) and toward the main Central Massif geanticline. Somewhat later, but still during the pre-Stefanian, the geanticline and its northern margin were split up by a meridional fault of the Grand Sillon Houiller.

An epi-Hercinian platform mantle, best developed in the Paris Basin was formed during the Permian. Together with the Central Massif "core", its northern margin was split up, in the Oligocene, by submeridional troughs of a "Baykal" type (Limagne, Foraise).

3. The southern margin of the Central Massif (south hercinid branch). By the beginning of the Devonian, the north slope of the Montagnes Noires, and presumably Rouergue, the southwest margin of Limousin, and most of the Cévennes constituted a province of uplifts which extended to the south the main Central Massif anticline ("core"), after the Caledonian folding (Figure 4).

The Devonian is known only from the south slope of the Montagnes Noires and in the south of the South Cévennes (Vigan). Locally, it rests transgressively on a folded and eroded Caledonian basement; in other places, conformably on the Gotlandian. Miogeosynclinal conditions, inherited from a remote past (Brioverian), persisted into the Devonian. In the middle and upper parts of the section, Devonian terrigenous clastic and carbonate deposits (600 to 750 m thick) are red. A sudden and rapid change from the miogeosynclinal to eugeosynclinal conditions is associated with the onset of the Carboniferous.

In the opinion of B. Géze [19], this change was determined by epeirogenic movements between the Devonian and the Dinantian. Associated with the Tournaisian is a local appearance of granite veins and flows of andesite and dacite lavas. In the southern part of the Montagnes Noires, Devonian and Dinantian sedimentation was uninterrupted. A thick Viséan section (about 1000 m) is represented by a Kulm "facies" which terminates the marine Paleozoic section.

The course of Hercinian orogeny was quite complex. Hercinian folding embraced the entire area of Devonian and Dinantian geosynclinal sedimentation as well as a zone of caledonids, north of the Montagnes Noires axis. Sudetan movements, according to Géze [19], produced sublatitudinal folds split up by thrusts into a number of plates. This folding was accompanied by granite intrusions. Subsequent faults produced granulitic pegmatite, aplite, then microgranitic rhyolite and possibly "bed-by-bed" intrusions in sedimentary series. A second phase (at the Namurian-Westphalian boundary) led to a number of "nappes" (Moutumé, south slope of Montagnes Noires, Vigan, southern Cévennes) to the north and northwest, i. e., toward the Central Massif ancient "core". Also correlative are terminal granite intrusions and doleritic lamprophyre veins. Later, prior to the end of Westphalian time, the mantle was folded, broken up into plates (Carbière), and pushed north and north-northwest. In pre-Stefanian time, major faults (Coss, Vilford) cut the Hercinian folded complex. Like the Grand Sillon Houiller, these fault zones became sites of deposition for Upper Carboniferous fresh-water coal measures. Flows of rhyolites, trachytes, and andesites are also of middle Stefanian age. Intensive local folding took place at the end of that time, as it did in the Central Massif. Permian deposits rest transgressively and unconformably either on deformed Stephanian beds or on older formations. This was the beginning of an epi-Hercinia

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[5] H. Stille's term.

platform mantle. The close of the Early Permian was marked by the appearance of quartz veins with a diversified mineralization (Lodevoix, Albigeois).

Echoes of the Pyrennean orogeny were expressed in weak undulations and in the development of a network of sublatitudinal normal faults, in the Late Cretaceous, Lutecian, Oligocene, and Miocene. Basalt flows penetrated these fractures, in the Miocene and Pliocene.

## III. The Vosges (northern hercinid branch)

Resting unconformably and transgressively on the Vosges folded metamorphic basement is a thick sequence of sedimentary and volcanic rocks (the Kulm "facies") of the Devonian and Dinantian, metamorphosed only at their contacts with the granites. The Kulm is gathered up into strongly compressed folds (Sudeten phase) with a Variscan trend (northeast) and cut by assorted (amphibole, dimacaceous) granites. Originating simultaneously was a new system of faults with a Variscan trend, which controlled the granulite intrusions. At the close of the Carboniferous, isolated minor depressions in the eroded Hercinian basement were sites of deposition for freshwater coal-bearing sediments, folded at the end of the Stefanian (Figures 4 and 5).

An epi-Hercinian platform mantle was initiated in the Permian, where terrigenous clastic deposits are interbedded with basic and acid (ignimbrites) extrusives; their formation continued in the Triassic and Jurassic. Later, the Vosges was involved in an arched uplift, split in the Paleogene by the meridional Rhine trough.

On the whole, the geologic history of the south Vosges is the same as for the northern margin of the Central Massif of France (Morvan, in northern Auvergne).

## IV. Schwarzwald

The Hercinian stage of Schwarzwald development is quite peculiar. As in the Vosges, post-Cadomian geanticlinal conditions in the north margin of the Central Massif and in Domnonea were sharply disturbed in the Devonian and Early Carboniferous. As in those provinces, the northern limb of the immense Moldanubicum geanticline, dissected by deep faults, subsided and was intensively reworked in the course of Hercinian folding. In the Schwarzwald, the intensity of this Hercinian reworking appears to have been greater than in any of the other Hercinian massifs of France. Curiously enough, the Upper Devonian and Dinantian sedimentary province was quite limited in the Schwarzwald [28, 29]. It was confined solely to a zone along a deep latitudinal fault, in the south Schwarzwald, extending from Badenweiler in the west to Lenzkirche in the east. Deposited in the Late Devonian and the beginning of the Dinantian, in a narrow but long "scar" trough within that zone, was a thick (about 1000 m) series of sedimentary rocks with prominent graywacke followed by shale, quartzite, black siliceous shale, and less common fine-grained sandstone and marl. A goniatite, collected from the upper part of the section, dated it as Upper Devonian to basal Dinantian. On the other hand, ganoid fishes were found in the same series, near Lenzkirche, thus suggesting lacustine sedimentary conditions.

The Upper Devonian is separated by angular unconformities from both the folded basement complex and the overlying Kulm. Associated with the Bretagne folding are a great alteration of the basement rocks throughout the Schwarzwald, the second stage of regional anatexis, and the formation of bodies of early Variscan granite, syenite-diorite syntectites, palingenites, and "marginal" granite extending along the northern limb of an Upper Devonian "scar" trough.

Phenomena of an early Hercinian (Bretagne) folding, anatexis, and granitization, affected the entire Schwarzwald ancient folded complex which was an erosion province in the Late Devonian, and a source of clastic material for a long and narrow "scar" trough. From all evidence, it was Bretonian movements that produced a system of northeasterly (Variscan trend) folds, well expressed throughout the Schwarzwald.

It follows that all these terminal Devonian phenomena took place under prevailing geanticlinal conditions, and appear to have been comparatively shallow. We have encountered an identical or similar example in our discussion of secondary (Hercinian) migmatization in the Cornouaille anticline in the extreme western part of Ligeria, near the convergence of the two Armorican faults.

Following these briefly described events which were related to Bretonian folding, a new Tournaisian and Viséan sedimentary series was deposited unconformably on underlying rocks, within the same "scar" trough. This is a comparatively thin (about 100 m) continental series of conglomerate, sandstone, arkose (locally bituminous), marly and bituminous shale, and limestone. The sandstones carry abundant plant remains. Locally present are thin coal beds altered to anthracite at the granite contact. Interbedded with sedimentary rocks in isolated segments of the trough are porphyry, tuff, and agglomerate.

The south Schwarzwald Dinantian is correlative (i.e., equivalent) to the Namurian, Westphalian, and Stefanian molasse of Armorica and the Central Massif.

Marine deposits (crinoid limestones) appear only in the extreme north of the Schwarzwald, in the Baden-Baden area, toward the top of the Viséan.

Sudeten folding, unlike the Bretonian, was apparently local. Associated with the close of the Viséan are numerous faults, a shaping-up of the "Kulm graben", and the last granite intrusion, including the "granulites", accompanied by a vein series with hydrothermal formations (Figures 4 and 5).

The formation of an epi-Hercinian platform mantle, an accumulation of red molasse in isolated troughs within the massif and especially along its periphery, and a flow of acid lavas (quartz porphyry) occurred during Permian time.

In the Tertiary, the Schwarzwald and the Vosges were parts of a mighty arched uplift cut by the meridional Rhine trough. In the Miocene, a volcanic Kaiserstuhl complex was formed at its bottom, including phonolite, tephrite, essexite, theralite, and carbonatites [28, 39].

## V. Odenwald (north hercinid branch)

The presence of Devonian and Lower Carboniferous deposits has not been established in the Odenwald. Only east of Darmstadt, slightly metamorphosed shale and subordinate metadiabase have been conditionally assigned to the Devonian. However, as in the Schwarzwald, the effect of Hercinian folding, metamorphism, and volcanism on the Odenwald folded basement is considerable.

Linear folded structures of a northeasterly (Erzgebirge) trend are distinct in the western part of the Odenwald (Bergstrasse). Their origin is usually associated with early phases of Hercinian folding. Ancient "Rhine" trends of folds in the Odenwald metamorphic basement complex have been almost obliterated by the hercinids. Associated with Hercinian folding is a recrystallization of Precambrian and lower Paleozoic pararocks, as well as the formation of large and numerous bodies of granodiorite, diorite, gabbro, and metasomatic quartz monzonite, formerly called "gromm-granite".

These bodies are spatially related to the large submeridional Otzberg fault zone which cuts the Odenwald in two. Widely developed in the fault zone are mylonites of at least two generations. This ancient Otzberg fault, had divided the Odenwald as early as the early Paleozoic, and appears to have played quite an important part in Hercinian orogeny. It maintained its activity in later times. Associated with it were Permian porphyry and of Tertiary basalt flows. A platform mantle, present in the Odenwald as in other massifs described above, was deformed along that fault (shifts in Triassic motley sandstone beds; [1, 36, 37].

## SUMMARY

1. An initial stage of geosynclinal development within this province of Western Europe was associated with the close of the Precambrian (Brioverian, Infra-Cambrian, Late Precambrian, Rhiphean, Sinian, Late Algonquian). Outlines of an Assintian folded province have been recently drawn by H. Stille [35]. However, some zones within it, such as the Armorican Trench, not affected by Cadomian folding, must be separated. The assumption that the Aquitanian syneclease is part of the assintid zone is doubtful; drilling data here reveal many features in common with the Montagnes Noires and south Cévennes hercinids. Likewise, there is little justification for including in the Assirtian zone all median massifs of the Western Alps, with a possible exception of the Mercantour massif, as pointed out by J. Jung [25].

A vast geosynclinal trough existing in the Brioverian was not uniform. Its western part (Armorica, Limousin) was a site of flysch accumulation. Miogeosynclinal conditions prevailed in the south (Montagnes Noires). In the northwest (Normandy), Brioverian eugeosynclinal deposits were thinner. The appearance of assorted tillites (marine and reworked tillites and banded shale) suggests the proximity of a cordillera.

2. Deep faults greatly affected the development of an immense Brioverian geosyncline (marginal faults of the Armorican Trench, and the Argentat fault in the Central Massif). They differentiated the various sedimentation zones, controlled the course of Cadomian (Assintian, early Baykalian) folding, and affected the orientation of the axes of folds and of granite bodies. These ancient faults, initiated in Brioverian time maintained their activity till the close of the Paleozoic.

3. Some formational features of the Brioverian series are noteworthy. Closely interwoven in it are a spilite-keratophyre and a flysch formation. The first has been commonly associated with initial phases of development of geosynclinal provinces; the second, with its terminal phases. It appears that these concepts are due for a revision inasmuch as the Brioverian series of France probably is not a unique phenomenon, as a formation. For instance, the lower Paleozoic of the Grampian highlands of Scotland exhibits the same combination of spilite-keratophyre flows and flysch [3].

4. The concept of linear folded structures disappearing in the interior of geosynclinal provinces, and of linear folds being jammed against the edges of platforms [7], too, has no

confirmation here. A linear folding is characteristic of Cadomian structures of Armorica, and the Central Massif "core", as well demonstrated by French geologists. Both these regions are located within a Brioverian geosynclinal trough.

5. A combination of northwesterly ("Armorican") and northeasterly ("Variscan") trends, present as an "arc" convex to the south, in the middle of the Central Massif of France, as noted by S. N. Bubnoff [1] long age, is quite old, having been formed during the Cadomian folding. The cause of this arcuate trend is not clear. It is possible that this is an ancient structural plan inherited from a remote Precambrian time, as is the case of the smooth change in the "Sayan" and "Baykal" trends near the south end of the Baykal.

6. A radical rebuilding of the entire geosynclinal province took place in the beginning of the Paleozoic. Post-Cadomian uplifts which affected nearly all of it, with the exception of the "Armorican Trench", created stable geanticlinal conditions in Domnonea, Ligeria, the Central Massif (with the exception of its southern margin), the southern part of the Vosges, in the Schwarzwald, and in the western (Bollstein) Odenwald. Uninterrupted geosynclinal sedimentation, inherited from the Brioverian, continued in the Armorican Trench, in the early Paleozoic, as it probably did in its eastern part buried under a Mesozoic-Cenozoic mantle of the Paris Basin, in the northern part of the Vosges, and in the Bergstrasse Odenwald. This is the north branch of a Paleozoic geosyncline. Located on the other side of a newly-formed geanticlinal province was a south branch of that geosyncline, including the southwestern part of Limousin, Rouergue, Montagnes Noires, Moutumé, and south Cévennes. Here, apparently, belong the present Aquitanian syneclease and a number of "outer" median massifs of the Western Alps, Belledonnes, Grand-Paradis, and Maure [25], with the exception of the Mercantour which forms in the east an isolated geanticline zone correlative with the "core" of the Central Massif of France.

In the middle Cambrian, the area of the northern geosynclinal branch was extended somewhat at the expense of Normania; in the Late Cambrian, at the expense of Ligeria; and in the Arenigian at the expense of Mancellia. Mass submarine lava flows occurred along deep marginal faults of the Trench, in the early Paleozoic. Ligeria was dissected by new faults, conductors of magmatic melts. These new "permeability zones",[6] early Paleozoic faults Redon-Montreuille and the Loire mouth — Fonteney-le-Comte — trend parallel or subparallel to the south Armorican marginal fault.

In all these areas of post-Cadomian uplift gradually reinvolved in geosynclinal subsidence, the lower Paleozoic rests transgressively on a deeply eroded folded (Cadomian) basement. In other words, these northern geosynclinal branches, newly-involved in a subsidence, should be called, unlike the Armorican Trench province and the south geosynclinal branch, "secondary" geosynclines, in the terminology of A. V. Peyve and V. M. Sinitsin [6].

The Paleozoic section in most of Ligeria is much thinner compared with the rest of Armorica, which suggests that Ligeria is the pericline of the main geanticlinal zone of the Central Massif, south Vosges, Schwarzwald, etc.

Eugeosynclinal conditions persisted in the Armorican Trench, as they did elsewhere in the north geosynclinal branch, during the early Paleozoic. Normania and Mancellia did not participate in that system. Here, miogeosynclinal conditions were initiated in the early Paleozoic. The south geosynclinal branch apparently maintained the earlier Brioverian miogeosynclinal conditions, with a single flash of volcanic activity at the Brioverian-Cambrian boundary.

7. Caledonian folding did not have regional significance, having been confined to the periphery of the south geosynclinal zone. Its linear folded structures (northern slope of the Montagnes Noires, Rouergue, Cévennes) were similar in their intensity to the contemporaneous Ardennes formations, as pointed out by B. Géze [19]. Caledonian folds are overturned to the north, toward the geanticline. A fringe of Caledonian folds forms a south accretion to the main anticline and emerged from the sea, in the course of the Paleozoic. Apparently related to Caledonian folding was the single-stage Rouergue migmatization which affected the lower, Brioverian parts of the geosynclinal section.

The reaction of the Central Massif geanticline to Caledonian movements in the south geosynclinal branch is quite interesting. Here, under geosynclinal conditions affecting the already metamorphosed Brioverian rocks, a second (pre-Devonian) stage of progressive metamorphism took place, producing second generation migmatites ("stratoid") and metasomatic formations [10, 11, 17, 31], along with non-linear gentle folds, swells, and "arcs", which complicated the structure of a Cadomian folded basement complex. And so, the old question arises, at what depth did the recurrent processes of migmatization, metamorphism, and metasomatism take place?

8. The Devonian was marked by most important events in the tectonic life of all these massifs. New faults originated in Domnonea, with a collapse of isolated and at times quite

[6] N. A. Streis' term.

large geanticlinal segments occurring in that province as well as in the northern limb of the Central Massif geanticline, in the south Vosges, and Schwarzwald. Devonian deposits were laid down transgressively on a deeply eroded Cadomian folded basement. It appears that a regimen of "secondary" geosynclines should have been established in collapsed parts of the geanticlinal as a matter of fact, typical eugeosynclinal conditions prevailed there, instead, along with a rapid accumulation of largely terrigenous clastic sequences (conglomerate, graywacke, arkose, siliceous rocks) closely interbedded with extrusives. The latter are locally represented by spilite-keratophyres (as in Lyonnais). Intruded in this sedimentary-volcanic body were basic and ultrabasic rocks, probably associated with newly-formed fairly similar to the Brevennes in the northeastern part of the Central Massif.

More subdued Devonian tectonic conditions prevailed in geosynclinal troughs inherited from the early Paleozoic, in the Armorican Trench, in the north of Ligeria (Quimper-Angers "basin"), on the Montagnes Noires south slope, and in the southern part of south Cévennes. Most of Ligeria preserved geanticlinal conditions of the early Paleozoic. In the Vendée, for instance, the Devonian is represented only by Givetian marine deposits.

At the Devonian-Dinantian boundary, Bretonian folding proceeded with different intensity in different segments of the geosynclinal province, being the most effective in Armorica. On either margin of the Central Massif, in the Vosges and the Schwarzwald, Bretonian folding is either altogether missing or merely local. Associated with Bretonian folding in Armorica was the initiation of a cluster of Hercinian folds, strongly compressed from the west, in the convergence area of deep faults, and diverging fan-like in the east. Bretonian folds are especially well expressed in the area of the Trench, Normania, and Domnonea [32]. Ligeria, along with the rest of the geanticlinal zone (except for the Schwarzwald) appears to have been excluded from Bretonian folding. In the Schwarzwald, a new Bretonian "suture" structure originated in the deep fault zone, along with a radical alteration in ancient basement rocks (second stage of regional anatexis; granitization; intrusion of "marginal" granites). The Schwarzwald Bretonian "suture" structure was a harbinger of a mass emergence of such structures in later stages of Hercinian orogeny, in France.

9. Of a greater regional importance was the Sudeten folding which witnessed a final shaping up of the basic folded structure familiar from geologic and tectonic maps which accompany the classic works of E. Suess, M. Bertrand, Ch. Barrroy, and later studies by L. De Lonne, E. Raguen, G. Goguel, A. Demey, etc. The coarse terrigenous deposits alternating with shale and limestone which carry much plant detritus, and the close association of these sedimentary formations with extrusives, are all typical of the Kulm "facies" widely distributed in all Hercinian massifs of France and south Germany. The lava flows are strictly confined to lines of pre-existing as well as new deep faults. Ligeria, the south part of Armorica, again demonstrated, in the Lower Carboniferous, its association with the geanticlinal zone; the marine Dinantian is completely absent, here. A marine transgression engulfed the Trench area, Domnonea, and Normania. Extrusives are missing in the Normanian Dinantian, a fact suggesting the preservation of miogeosynclinal conditions inherited from a preceding early Paleozoic stage.

In the western part of Armorica (Cornouailles) a new stage of regional metamorphism and migmatization was associated with initial phases of the hercinids, also a development of granite bodies. Large Hercinian granite intrusions originated in Ligeria and in the Trench area. The combination of metamorphic, migmatization, and granitization processes here are similar to those in the Schwarzwald. There is the suggestion of a connection between the higher intensity of these processes in the east and west sides of this system, on one hand, and the more important deep fault zones, on the other. In the north limb of the Central Massif, foundered as early as the Devonian, the Hercinian metamorphism is considerably less intensiv The Brioverian basement complex has suffered only a much weaker retrograde metamorphism (Lyonnais).

A higher activity in the Hercinian tectogenic stage, observed nearly everywhere, was quite conspicuous in the south geosynclinal branch, as well. Eugeosynclinal conditions prevailed here in the Dinantian, for the first time since the Brioverian.

The reaction of the geanticlinal "core" of the Central Massif to early Hercinian movements in adjacent geosynclines were expressed chiefly in huge granite intrusions of the Millevache, Marjeride, and Bram types. It has been established that many of them are directly related to both the ancient Argentat fault and with younger faults of Limousin and other areas.

The Sudeten folding proceeded against the background of a general uplift in geosynclinal zones, under formative conditions of mountain relief. It is natural that "suture" structures confined to deep fault zones were widely developed in such a peculiar environment. They are best represented by the Chateaulin-Laval and Quimper-Angers synclines, clearly delineating the zones of the two main faults of Armorica; by a zone of the Schwarzwald Kulm; etc.

Developed on both limbs of the Central Massi

geanticlinal "core" is a system of linear folded structures, cut by thrusts. The thrust movement was toward the geanticlinal axis. This phenomenon is quite well expressed in the northern part (the Egurand Plateau and Sioule thrusts) as well as in the south (Montagnes Noires, South Cévennes). In this southern branch of hercinids, Sudeten folding affected not only the province of a late Paleozoic geosynclinal trough but radically reworked a previously consolidated fringe of caledonids which had extended to the south geanticlinal wing. This curious fact, suggesting a high intensity of Hercinian tectogenesis, stresses at the same time the possibility of an intensive reworking, through folding, for previously consolidated provinces. Similar phenomena have been observed in folded zones of other ages, such as the north foothills of Scotland, a province of early Paleozoic marginal uplifts, intensively reworked in the course of Caledonian folding [3].

The Sudeten folding, responsible for the famed system of Armorican and Variscan trends, repeated in general features and after a long time interval the Cadomian structural plan; in that sense, it must be assigned to regionally inherited structures.

10. The concluding Hercinian stages were expressed as a rule by the fracturing of newly-created mountain structures; by the origin of a new system of faults, especially well defined in the Central Massif (Grand Sillon Houiller); and by an accumulation of coal-bearing and other molasse in zones of old and new faults.

The Erzgebirge, Asturian, and Saal folding phases were mostly local, better expressed only in zones of deep faults and in the folding of continental molasse, including the coal-bearing (Figure 6). Metamorphic phenomena are missing. Igneous activity was quite weak and local.


FIGURE 6. The nature of deformation in the Upper Carboniferous (Stefanian) deposits of the Ste. Étienne "scar" downwarp (Grand Sillon Houiller), after G. Goguel.

11. The inconsistency in tectonic processes for individual segments of the geosynclinal province, apparent as early as the Brioverian, became more conspicuous with time, and reached its maximum in the Dinantian. The establishment of platform conditions, as well as the formation of a lower stage of the platform mantle, are generally associated with the beginning of the Permian; in some places, however, such as in Normandy, the Permian is conformable on Upper Carboniferous deposits, and the age of basal mantle beds is correspondingly lower.

12. Initial stages of the platform regiman were not quite quiescent, tectonically, as witness the Saalian movements which intensively squeezed Permian redbeds; also a vigorous volcanic activity in the Permian and locally in the Triassic (Domnonea, Vosges, Schwarzwald, and Odenwald). Associated with the Permian in the south hercinid branch is the formation of quartz veins with an assorted mineralization.

13. Being unable to describe in this paper the most interesting platform stage of Hercinian massifs of France and South Germany, we only note that all these massifs, following a liquidation of geosynclinal conditions in the second half of the Carboniferous, have lost their identity as parts of a geosynclinal province. The Central Massif, the Vosges, the Schwarzwald and Odenwald, have played the same part in the history of the epi-Hercinian Armorican platform as the shields of ancient platforms; in so doing, they have displayed a steady tendency for uplift, thereby meriting a special nomenclature. "Paraspis"[7] perhaps would be the most appropriate term. Like the ancient shield of East Africa and East Siberia, these shields became in the Tertiary the sites of development of immense troughs of the Baykal type (Limagne, Foraise, Rhône, and Saône, the Swiss molasse zone, the Alsace "plain") which eventually became grabens. This development stage, interesting in terms of comparative tectonics, deserves special study. In the Cenozoic there was another manifestation of volcanism in all of the tectonically different parts of the Central Massif, in the Rhine trough, and in the Odenwald. Quaternary glacial phenomena are common. The continuing uplift of

[7]Para = almost; aspis = small shield (Greek).

these massifs is suggested also by their young relief and seismicity.

In conclusion, it must be stated that S. N. Bubnoff's term, "Franco-Podolia", appears to be devoid of content. The terminal folding of the Russian Platform is known to be quite old (Karelian, pre-Cadomian, pre-Assintian, pre-Baykalian). The massifs of France and South Germany, briefly described here, and probably also the Czech massif, were combined into a "Moldanubian block" at a much later time, between the Precambrian and the early Paleozoic.

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# PALEOMYCOLOGY - A NEW TREND IN MICROSCOPIC STUDY OF COALS[1]

by

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Up to the present time, the fact that coal preserves carbonized remains of petrified molds and fungi has not been considered in paleobotanical study. We believe feasible paleomycologic studies of coal, by almost the same methods as used in palinologic study based on that of spores (Sporae dispersae) of higher plants. Palinology is based on the technique of maceration of spores and pollen; the basis of paleomycology is a petrographic method of studying polished sections of coal.

The polished section method, popular mostly in Europe and to a smaller extent in the U.S.S.R. and U. S., does not afford the means, as the maceration method does, of studying isolated and intact fossils but merely their variously oriented sections. This, of course, is an important shortcoming of this method, which opens it to substantial criticism. It should be noted, however, that separation of mycologic elements from coal or from mixed carbonaceous sediments, by maceration, has not yet brought any substantial results. To be sure, the content of these elements in fossils is much lower than that, say, of spores. Furthermore, the present methods have been used quite successfully in coal petrography, especially after 1955. It must be admitted that polished sections are more effective in the study of remains of mycologic elements than are thin sections, because they reveal clearly the morphologic details.

Coal petrographers who ordinarily do not pursue microfloral study usually describe as sclerotinites or simply as opaque material, the elements of mycologic origin which they see in polished sections; in some instances, they erroneously assign them to semi-fusinite and fusinite.

Some authors (e. g., the Polish student A. Drath; [7]) use such terms as chitinite and semi-chitinite for sclerotia preserved in fungi coal. This terminology obviously emphasizes the presence of chitinous material in mycologic fossils.

In western literature, specifically with E. Stach, we encounter the term, "fungi micrinite" (Pilzmikrinit); this means that the author regards some nontransparent coal particles to be of mycologic origin.

On the basis of personal observations, this author has come to the conclusion that some non-transparent particles of micrinite nature are in fact altered and broken up fungi tissue. In such instances, the term, "fungi micrinite", should be regarded as correct. Micrinite similar to that identified by E. Stach from the Ruhr basin coal has been identified by the author in beds of the Upper Silesian basin. A correct determination of the mycologic origin of coal is rather difficult, although feasible with fair accuracy, after some experience.

In studying coal polished sections, the following criteria may be regarded as typical of a mycologic origin:

1) A high degree of light reflection by sclerotinite, although varying in a broad range. Some authors explain this phenomenon by chitinization; others by generic properties of individual samples.

2) A difference in the abrasive and sclerometric hardness of specimens. As a rule, sclerometric hardness increases with reflectivity.

3) Microscopic dimensions (from a few to 1000 microns) of particles preserved in coal. These particles are rarely larger than 1 mm.

4) Sclerotine largely is the remains of higher fungi, such as conidia, conidiophores, asci, basidiospores, fungi sclerotia, individual hyphae, mycelia, fruit-bearing elements, etc.

5) The form and structure of these fungi is quite diversified.

6) Sclerotinite or guninite (the latter term

[1] Paleomikologiya novoye napravleniye mikroskopicheskikh issledovaniy ugley.

stresses the botanical aspect of these components) occurs most often in durain or clarain-durain humolithic facies, from the Paleozoic through the Tertiary. However, it has been identified only in sapropelites (such as the genetically interesting boghead fácies from the Upper Silesian basin, and in a fairly large amount). Funginite is rare in cannel coal.

7) The sclerotinite content in coal beds is inconsistent, probably due to their conditions of formation. Equally inconsistent is its distribution in individual beds.

8) Maximum amount of fossil fungi is present in the so-called dry bogs.

## SYSTEMATICS OF FOSSIL COAL-FORMING FUNGI

In our earlier works [1] we advocated the necessity for paleomycologic schemes to reflect the systematics of the so-called permanent formations, fungi sclerotia, on one hand; and of reproduction organs, on the other. Such a basic scheme will be as follows:

| Sclerotinite (petrographic term) | Funginite (paleobotanical term) |
|---|---|
| Fungisclerotites or Fungisclerotes | Fungisporonites<br>Anteturma Sporonites (R. Pot) Ibr., 1953.<br>Turma Ascinae Beneš, 1956<br>Sporinae Beneš, 1956<br>Basidinae Beneš, 1856 |

We prepose to assign largely fungi sclerotia to the Fungisclerotites group; and sporogenic elements to the Fungisporonites group. Systematics of the Fungisclerotes group has been already worked out, partially. In 1957, E. Stach and W. Pickardt compiled a morphologic scheme of Paleozoic sclerotia, establishing eight artificial formal genera, as the first stage, (Crenasclerotes, Cellulasclerotes, Globosasclerotes, Spongiasclerotes, Pillulasclerotes, etc.). Other genera were described later on. This author has described new genera from the Upper Silesian basin: Sulcatisclerotis, Viperisclerotis, Stellasclerotes, etc. Some students have already started a partial description and systematization of spore-bearing formations.

The time is ripe for working out a single nomenclature and the principles of its construction: it appears from the literature that some authors have the tendency to include sporogenic organs, i. e., elements of the Fungisporonites group, in the Stach-Pickardt sclerotia system (always ending by sclerotes). These systematic fallacies are explained, on one hand, by shortcomings in the paleomycologic studies of coal and, on the other hand, by the inadequate knowledge of distinctive features in the anatomy and morphology of the fossils classified.

## SOME RECENT ACHIEVEMENTS IN PALEOMYCOLOGY

The results of recent study of lower plants, e. g., molds and fungi, have shown that some fungi, such as phycomycetes and ascomycetes, existed as early as the Carboniferous; it may be assumed, then, that these microorganisms had appeared in pre-Carboniferous time.

For the time being, the oldest mycologic elements have been identified by petrographic methods only in Lower Carboniferous (Dinantian) coals from the Moscow basin. It goes without saying that now it becomes necessary to study older coals for that purpose. It is important to note in this connection that a maximum genetic and specific variety, in Europe, has been observed in the Westphalian stage, which is positive proof of an immense quantitative and qualitative development of the highly organized vegetation of that time. Our personal observations have revealed an impoverishment in forms, quantitatively but mostly qualitatively, in Namurian C — B — Z and in the Lower Carboniferous.

Coals of the Stefanian (Uralian) stage are but little known as yet; Permian coals, on the basis of studies of fungi-durain in the Kuznetsk basin, are marked by a small variety in genera and species of fossil fungi. This suggests that from the Westphalian to the Permian, plant forms became poorer qualitatively rather than quantitatively, so that some Kuznetsk basin durains are marked by a high content of mycologic elements, for which reason we are fully justified in assigning them to a new coal petrographic facies of fungi-durain.

Our assumption of a qualitative impoverishment of funginite in the pre-Permian is purely speculative, requiring further paleomycologic study.

All that can be said now is that the study of Upper Paleozoic coals has yielded the most data on some ascomycetes, because the assorted

FIGURE 1. Sclerotia and sporogenic organs of some ascomycetes from Carboniferous and Permian coal beds (Upper Silesian and Kuznetsk basins)

FIGURE 2. Remains of fossil fungi from Mesozoic coals (Cretaceous of Czechoslovakia)

ascoid and conidium spore-bearing fossils belong to those particular forms. Interesting results have been obtained from the study of the evolution of fossil asci from ascogenic hyphae; various forms of such asci or conidium fossils have been discovered, and it was occasionally possible to determine the sequence of evolution in some species.

The presence of fossil remains in Mesozoic and Tertiary coals testifies to the existence of certain basidiomycetes fungi in those periods, as well. In addition to sclerotium fungi, these coals contain diversified types of resting spores, uredospores, etc. Illustrated in Figures 1, 2 and 3 are but a few of the numerous Paleozoic, Mesozoic, and Tertiary sclerotium fungi or sporogenic formations, copied from microphotographs.

northern Czechoslovakia). Similar findings have been cited by other authors, for instance by M. Teichmuller, from German coals.

Tertiary fungi sclerotia and sporogenic organs have been observed, for the time being, mostly in brown coals of India, Indonesia, Germany, and Czechoslovakia. Mesozoic coals have been but little studied, paleomycologically, and even Paleozoic and Tertiary coals are not well known. For this reason, it is impossible, as yet, to make final conclusions on the stratigraphic significance of paleomycologic findings.

Some coals formed in a comparatively humid environment or a dry climate, contain many remains of saprophytic and at times even parasitic fungi. I assign such coals and seams to the fungi-durain group; they are present in

FIGURE 3. Remains of fossil fungi from the Miocene brown coal of Czechoslovakia

## RESULTS OF STRATIGRAPHIC STUDIES

The Paleozoic assemblage of fossil fungi is quite different from the Tertiary. Present in Mesozoic and Tertiary coals are representatives of basidiomycetes, such as resting spores from Cretaceous coals of Czechoslovakia and even from the Jurassic (Liassic). Definitely proven on the basis of a finding of resting spores and uredospores has been the presence of Uredinales from the basidiomycetes group. Fossil remains of Uredinales and Ustilaginideae are fairly numerous in coal facies of reed and grass marshes (such as the Anejca Miocene bed in

the Kuznetsk basin Permian. Thus, fungi-durain beds are components of continental coal facies and suggest active oxidizing processes in peat, and the accompanying activity of aerobic bacteria.

Strictly speaking, the remains of molds and fungi preserved in coal are the only evidence of a little known stage of biochemical change in the plant substance of ancient peat bogs. The study of this substance clarifies the nature of the coal forming processes at its early stages and of the effect on it of the decomposition of microorganisms.

At present, we have identified many more fossil fungi than before; it becomes possible, therefore, to outline methods for their correct identification. Thus, we are justified in stating that coal-petrographic methods have provided means for a systematic study of carbonized part of these lower plants.

## CONCLUSIONS

Microscopic study of coal is essential not only in coal geology but in paleobotany, as well. Formerly, coal petrography assisted the development of palynology (cuticular analysis); now it has led directly to the study of carbonized fossil remains of molds and fungi in coals (paleomycologic analysis). It is quite obvious that coal beds are concentrators of a multitude of forms of an extinct plant life, very valuable to science as a primitive flora. Present-day microscopy has been perfected to such an extent as to make it possible to differentiate various microscopic objects. Present-day literature already shows the tendency for a paleontologic identification and description of such objects; however, these works are rather sporadic, as yet. As far as is known, most progress has been made in the study of Paleozoic molds and fungi; but this study must be extended to all basins of the world and to deposits of all ages, in order to obtain the diversified material necessary for theoretical generalizations.

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# SOME PROBLEMS IN FRACTURING TECTONICS OF THE AKTYUZ ORE FIELD[1]

by

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## BRIEF GEOLOGICAL OUTLINE

The Aktyuz ore field is located on the slope of the Trans-Ili Alatau. Involved in its structure are Precambrian crystalline schists (gneiss and green amphibole schist) cut by large massifs of Caledonian granite and associated series of vein rocks. Exposed among younger igneous formations is a late Variscan fracture intrusion of alaskite granite as well as small stocks of fine-grained porphyritic alaskite granite and old and young granophyres. Closely related to the latter are irregular bodies and dikes of aplite, syenite aplite, and albitite, and dikes of porphyrite and diabase porphyrite.

The crystalline schists are compressed into a tight synclinal fold whose axis trends northeast. Its axial part is complicated by a second-order isoclinal anticlinal fold.

Rocks in the ore deposits are cut by numerous faults, with northeastern to latitudinal trend. There are a few minor meridional and northwesterly faults (Figure 1).

Present within the ore field is a series of peculiar columnar bodies of brecciated rocks located in the top of the northeasterly dipping alaskite massif, along one of the northeasterly faults. Isolated columnar bodies occur above the alaskite domes, where the northeasterly fault controlling them is intersected by smaller latitudinal to occasionally northwesterly faults.

These columns appear founded in a horizontal cross-section. Most common are oval, broadened sickle-like, and pear-shaped sections. They are 80 to 300 m long, 40 to 180 m wide, and 350 to 400 m deep, being filled up with fragments of the enclosing crystalline schists; by stock-like bodies of fine-grained porphyritic alaskite granite and old and young granophyres; irregular bodies and dikes of aplite, syenite aplite, and albitite; and locally by dikes of porphyrite and diabase porphyrite. Post-igneous mineralization and lead and rare metal ore bodies are widely developed.

The rounded horizontal section of these columns, as well as the peculiar breccias filling them and some other features which we will not discuss here, suggest that their origin is related to a breakthrough of gasses accumulated in deep reaches of the alaskite massif, and that they can be assigned to typical explosion vents. A more detailed description of the structure and history of these columnar bodies can be found in a special paper [7].

## FRACTURES IN ORE DEPOSITS

Rocks of the Aktyuz field are cut by a dense network of large and small fractures: trending steeply-dipping northeasterly, northwesterly, latitudinally, and meridionally; also gently dipping, almost horizontal ones. The steeply-dipping northeasterly trending fractures are extremely rare in the crystalline schist (gneiss and green amphibole schist), which appears to be due to the mechanical anisotropy of these rocks, related to their high schistosity. Their steeply dipping schistosity planes have a northeasterly trend.

The transition from one system of fractures to another is gradual, in most instances; in the absence of such transitions, each system displays a large fanlike spreading of the fractures, both along the strike and the dip.

In studying the orientation diagrams for fractures, our attention was attracted not by their incipient systems alone, with their average elements of occurrence, and the spreading strike and dip fan, but with general features of the diagram structure. Characteristically, in a vast majority of the diagrams, the fracture orientation is zoned or nearly so. Considerably less common are diagrams with more or less isolated and, as a rule, vague maxima reflecting the fracture systems with a large strike and dip scattering fan.

There are two types of zonal diagram

[1]Nekotoryye voprosy treshchinnoy tektoniki aktyuzskogo rudnogo polya.

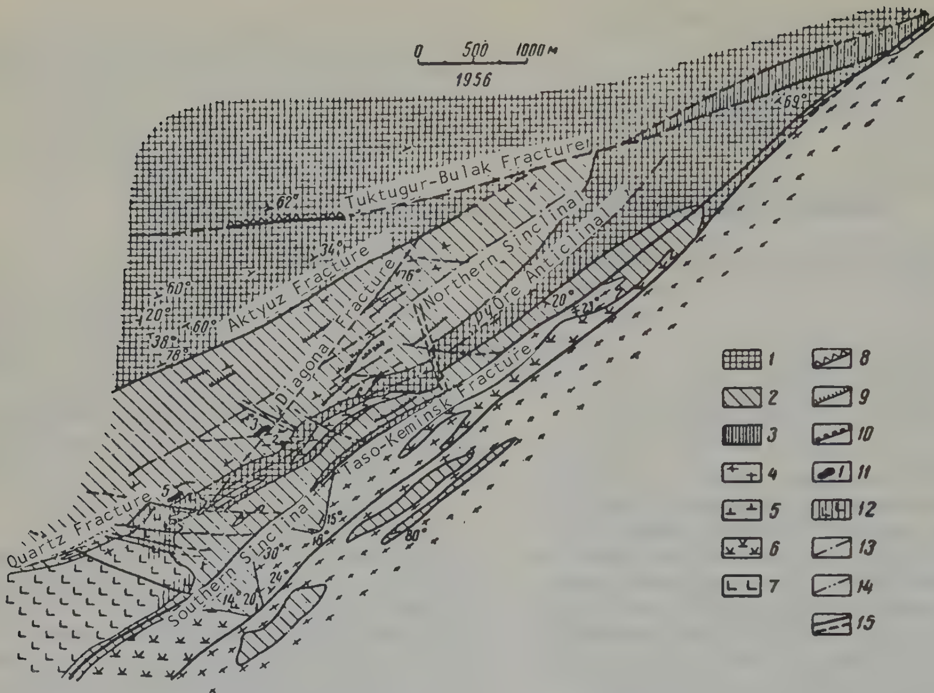


FIGURE 1. Structural map of the Aktyuz ore field. Compiled by V.A. Nevskiy from data of F.Sh. Radzhabov, N.D. Tikhomirov, and others.

1 - Gneiss; 2 - Lower Carboniferous green amphibole schist; 3 - porphyry and tuff; extrusive rocks; 4 - gneissic granodiorite; 5 - diorite and monzonite-diorite; 6 - syenite; 7 - alaskite granite; 8 - basic quartz porphyry; 9 - porphyrite; 10 - clastic dikes; 11 - columnar bodies; 12 - greisen and greisen-like granite; 13 - synclinal axes; 14 - anticlinal axes; 15 - faults.

structures. In the first, a belt of fracture poles bisects the diagram into two uneven halves. Such zones are very similar to zones of a single fracture trend but with quite diversified dips, from vertical or nearly so to horizontal. Diagrams of this type are characteristic of crystalline schist and occasionally of certain other rocks.

Another type of zoned diagram is characterized by a belt of poles for fractures of every trend but with a more or less uniform, often nearly vertical, dip. Such diagrams characterize the regularities in the spatial orientation of fractures in various rocks occurring in the columnar bodies and in alaskite granite. They have been observed, among other places, in narrow bands of crystalline schist about and above the columnar bodies, at their contact with the alaskite granite massif, and in some other rocks.

Fractures in crystalline schists. Minor fractures in these rocks have been studied in ten localities. A reduction of data so obtained has revealed a close spatial relationship in the orientation of schistosity planes and that of fractures which cut the schists. Most common are steeply-dipping northwesterly trending fractures oriented across the schistosity planes. Considerably developed also are diagonal, relatively steep fractures, meridional to latitudinal and nearly so, as well as a system of gently dipping fractures almost normal to the dip of the schistosity planes. Present in areas of local change in the orientation of these schistosity planes in crystalline schists are the corresponding changes in the orientation of fractures which cut them.

Present as a rule between these systems of fractures are gradual transitions, from vertical or nearly so, with a northwesterly trend, to fairly steep but becoming more gently-dipping, latitudinal to meridional, and then to gently dipping. For this reason, the orientation diagrams for fractures in crystalline schists are most often zoned or nearly so.

Figure 2 presents a typical orientation diagram for fractures in the crystalline schist. A belt of the fracture poles in this diagram is bent in a direction opposite to the schistosity pole and bisects the diagram into two uneven halves. Located in this belt are three concentrated elongated maxima: maximum I reflects a system of largely latitudinal to sublatitudinal fractures with a considerable fan-shaped spread of


FIGURE 2. Orientation diagram for fractures in crystalline schist at a considerable distance from columnar bodies. I, II, III — maxima of the fracture poles.

strikes and dips; maxima II and III characterize a system of northwesterly fractures with vertical to fairly steep northeasterly and southwesterly dips.

Some fracture orientation diagrams for crystalline schist exhibit isolated, usually vague maxima or groups of maxima; however, the latter always fall within the belt.

Characteristically, the fracture orientation diagrams obtained from the processing of measurements in crystalline schist, in locations near the columnar bodies (60 to 70 m away), have a more complicated structure. Appearing here along with a polar belt for fractures of the same type as in Figure 2, are new and steep fractures extending beyond the belt. Diagrams drawn from measuring the fractures on locations 10 to 20 m away from the columnar bodies are similar to the corresponding diagrams of the latter (Figure 3). They exhibit five definite maxima, generally greatly elongated. Maximum I reflects a system of vertical or nearly vertical fractures, mostly meridional; maximum II reflects similar fractures of latitudinal trend; maxima III to V designate steep northwesterly fractures.

Definite offsets in porphyrite dikes are often present along large fractures in crystalline schist. More specifically, left lateral shifts (1 to 1.5 m) have been observed along the meridional and nearly meridional fractures; and right lateral offsets along the latitudinal fractures. Locally present on the displacement surfaces are slickensides with horizontal or nearly horizontal striations. These data, supported by the observed offsets in porphyrite dikes of various angles and directions of dip, definitely suggest that lateral movements took

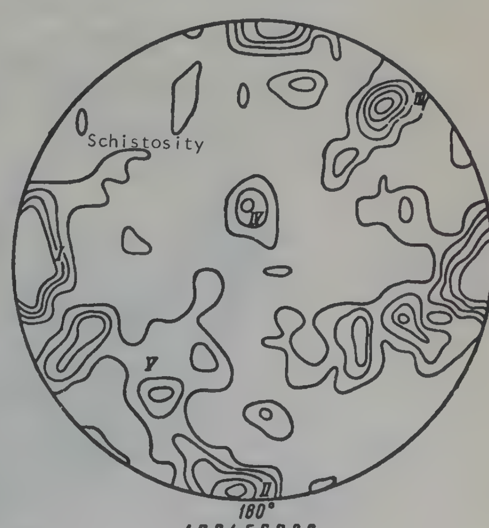


FIGURE 3. Orientation diagram for fractures in crystalline schist, 20 m away from the columnar body.

place along these meridional and latitudinal fracture systems.

The visible displacement in porphyrite dikes along major steep, northwesterly trending fractures is not the same everywhere. In some places, it is left lateral; in others, it is the opposite. An analysis of the numerous data on the displacement of dikes of various positions suggests either lateral thrust or lateral normal faulting.

Fractures in rocks filling up the columnar bodies. Orientation diagrams for minor fractures whose elements of occurrence have been measured in limited areas within the columnar bodies, and for major ones studied on different levels of mining works, have a zoned or nearly zoned structure. Considerably less common are diagrams with isolated maxima within such zones. Two to three maxima usually stand out on the background of a polar belt for fractures of various trends but with the same steep, commonly almost vertical dip; they reflect the prevailing development in a given section of various fracture systems which form gradual transitions. Most common are steep latitudinal, meridional, and northeasterly fractures; less commonly northwesterly ones. Present as a rule in the central part of a diagram are maxima corresponding to steeply dipping, in places almost horizontal, fractures.

Figure 4 illustrates a typical orientation diagram for major fractures in a horizontal section of one of the columnar bodies (141 measurements). It shows the wide distribution here of steeply dipping to vertical fractures of various trends, with latitudinal and sublatitudinal trends predominating. An exception is the northwesterly fractures with a steep northeasterly dip, which are comparatively rare. Consequently, the polar belt for fractures in this diagram is broken up in its northeastern quadrant.

An analysis of the level-by-level sections of individual columnar bodies immediately reveals the tendency of large fractures to be concentrated along the periphery of the column. Steep fractures, nearly radial or trending along the circumference chords are usually present in the contact zone. Also typical are fractures tangential to the circumference. Some of these are vertical; some others dip at 60 to 70° toward the center; still others dip at the same angles in an opposite direction. Figure 5 illustrates the distribution of major fractures at Horizon 3 of one of the Aktyuz columnar bodies. By far, most fractures here are distributed in near-contact segments of the column, with tangential fractures shown in its northeastern and southwestern parts.

A concentration of small fractures is often conspicuous along the periphery of the columns, as reflected in annular and semi-annular fringes of a coarse clastic breccia, often appearing to encircle the columns. These fringes are a few meters thick, locally 20 to 30 m, in larger columns. Present in some columns are semi-annular porphyrite dikes and conical vein-like bodies of early high-temperature quartz. These semi-annular porphyrite dikes in the enclosing

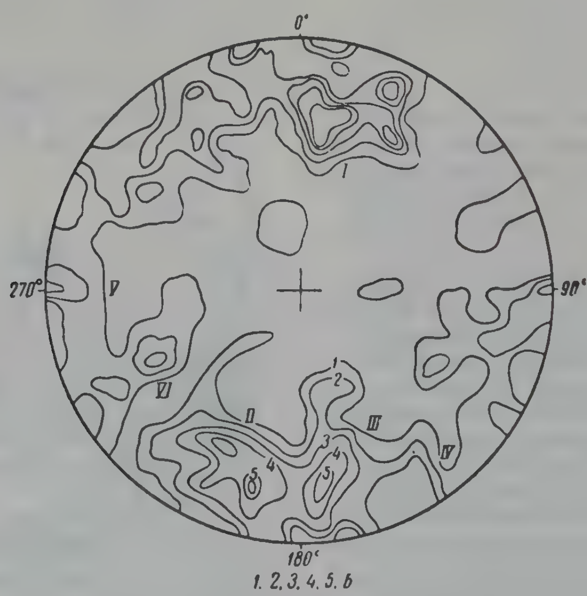


FIGURE 4. Orientation diagram for fractures over the entire area of the horizontal section of a tabular body.

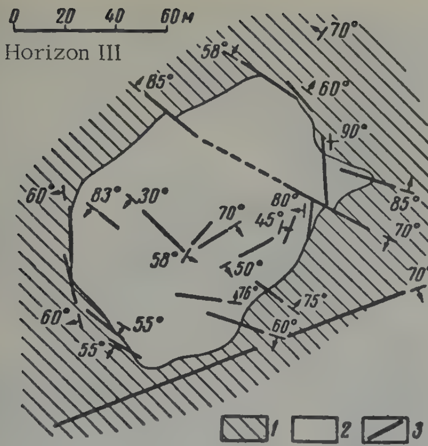


FIGURE 5. Distribution of large fractures in a columnar body of the Aktyuz ore deposit.

1 - green amphibole schist; 2 - columnar body; 3 - large fractures.

crystalline schist locally appear to encircle the columnar bodies.

These data show that annular and semi-annular zones of more intensive fracturing are distributed in the enclosing rocks and in central parts of the columnar bodies, as well as along their periphery.

The major fractures in columnar bodies are of various ages. The earliest are associated with initial stages of column formation. Present along them are vein-like bodies of early high-temperature quartz, dikes of granophyre and aplite, and other rocks. Associated with the youngest ones are vein-like bodies of drusy quartz with subordinate fluorite and calcite, with complete mineralization process in the Aktyuz ore deposits. Still younger fractures intersect and offset these bodies.

The peculiar distribution of pre-ore and intra-ore fractures in the column bodies had a decisive effect on regularities in the distribution of mineralization in them as well as on the morphology and occurrence conditions of the ore bodies. More specifically, quite typical of the Aktyuz ore deposits are semi-annular vein-like bodies and warped veins and lenses. Very common here also are irregular metasomatic deposits and pockets associated with the intersections and junctions of veins of all trends. A consecutive development of the annular and semi-annular zones of crushing has determined, in many places, the concentrically zoned distribution of mineralization in the columns.

Out of the entire post-igneous mineralization in the Aktyuz deposits, the youngest veins of drusy quartz alone are not related to the crushing zones. They always follow the trend of steep northeasterly trending zones of crushing and are found in both the columnar bodies and near them in the enclosing rocks.

Small displacements have been observed along many large fractures in the columnar bodies. Specifically, some of the largest meridional, latitudinal, and northwesterly fractures locally intersect and offset the contacts of these bodies by as much as 2 to 3 m, and occasionally more (Figure 5). The direction of shift is identical with that for the same systems of related fractures cutting the crystalline schist.

Occurring along the steep tangential fractures, in a number of places, are minor displacements (1 to 2 m), either normal or reverse. Similar small displacements are often associated with large, steep (35 to 45°) fractures.

These regularities in the orientation and spatial distribution of fractures in the Aktyuz columnar bodies are typical of the explosion vents of diamond-bearing kimberlite and of columnar bodies of basic and ultrabasic rocks in carbonatite deposits, as well as of necks, batholiths, and other columnar bodies of igneous rocks.

Presented in Figure 6 is an orientation diagram for fractures in the "Leningrad" kimberlite column, borrowed from A. M. Krutoyarskiy [3]. Figure 7 illustrates an orientation diagram drawn by A. A. Frolov for large fractures in


FIGURE 6. Orientation diagram for fractures in the "Leningrad" kimberlite vent, Yakutia.

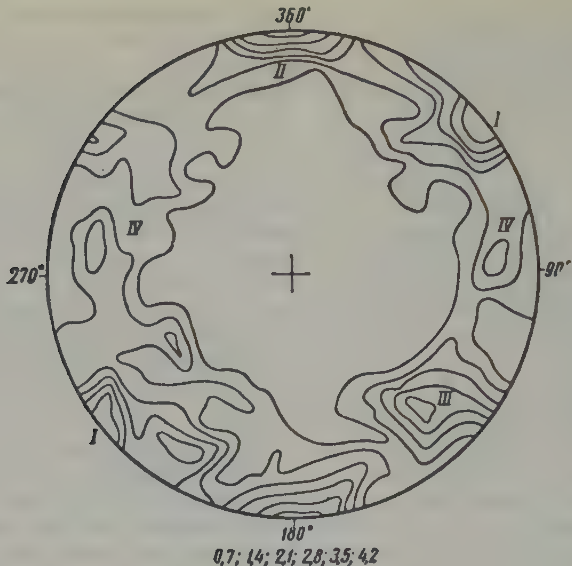


FIGURE 7. Orientation diagram for fractures in a carbonatite deposit.

the columnar body of one of the west Sayan carbonatite deposits.

Annular faults in craters and calderas of many volcanoes are well known. Quite interesting also are the so-called hidden volcanic structures represented by domes of sedimentary rocks, dissected by radial and tangeatial fractures (Figure 9). Most students associate the origin of hidden volcanic structures with a breakthrough of volcanic gases or with vertical pressure of magmatic melts intruded into deeper reaches of the crust.

Fractures in the alaskite granite massif. Orientation diagrams of both large and small fractures cutting the alaskite granite massif are zoned with regard to the disposition of poles of


FIGURE 8. Orientation diagram for fractures in the alaskite granite massif.

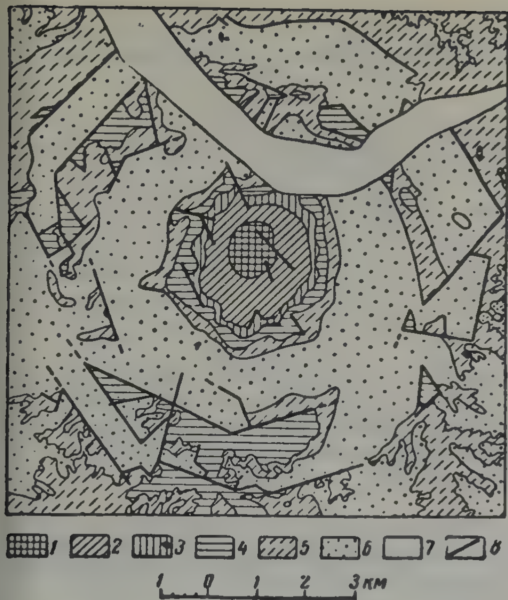

FIGURE 9. Geologic map of Wells Creek, Tennessee. After W.H. Bucher

1 - Lower Ordovician; 2 - Middle Ordovician; 3 - Silurian-Devonian; 4 - Lower Mississippian; 7 - Quaternary deposits; 8 - faults.

fractures of different trends but with uniformly steep dip. Each belt contains two or three maxima characterizing the most common distribution in a given segment, of fractures with meridional, latitudinal, or northwesterly trends. Present as a rule in central parts of the diagrams are one to two maxima reflecting gently dipping fractures in alaskite.

A diagram drawn from the measurements of fractures in alaskite granite (Figure 8) indicates a predominant development of steep fractures, including the vertical, of every trend. The comparatively weak maxima II, III, IV, and V, alone, emphasize a predominance of steep meridional, northeasterly and northwesterly fractures. Maximum I and other weaker ones reflect a wide development of gently dipping to horizontal fractures.

Prototectonic elements have not been observed in the granites, making it impossible to ascertain any connection between the orientation of fractures and flow surfaces. Nor are there any other regularities in the spatial distribution of fractures.

Fractures cutting the alaskite massif vary greatly in relative age. Present along the earliest of them are aplite dikes, vein-like bodies of early high-temperature quartz, and zones of sericitization and greisenization. Associated with younger fractures are dikes of diabase porphyrite and veins of younger drusy quartz with irregular accumulations of pale-colored fluorite and occasional calcite. No definite sequence in the development of fractures in the granite has been observed.

Quartz veins and greisenization zones along the large and steep meridional, latitudinal, and northwesterly fractures are commonly offset by 2 to 3 m. The directions of these displacements are quite similar to those observed along the same fracture system in the crystalline schist.

We have studied small fractures in dikes of diabase porphyrite, in quartz veins, and in greisen zones in the granite. Their orientation is the same in the porphyrite dikes as it is in veins of younger drusy quartz, when the latter are found in crystalline schist, near the alaskite granite or near the columnar bodies. The same rocks exposed at a considerable distance away from both are characterized by zoned fracture orientation diagrams typical of crystalline schist.

The predominance of steep fractures of various trends is typical not of the Aktyuz alaskite granite massif alone. Similar systems of fractures have been observed in intrusions and in large dikes associated with faults, in many other regions. The author has seen them in the Kara-Dzhilgin granite massif, on the south slope of the Kirghiz Range; in stock- and dike-like bodies of granodiorite, syenite porphyry, and other rocks of the Okurtau Range in the Kuramin Mountains; in quartz porphyry dikes of the Kurgan River basin, on the south slope of the Talas Alatau; and in other areas. Similar systems of variously trending steep fractures are characteristic of the stock-like massif of Jurassic granite porphyry in one of the east Sayan ore fields [5], and of the granite massif in one of the north Kazakhstan regions [6].

Steep dikes of porphyrite and diabase porphyrite are widely developed within the Aktyuz ore field, in crystalline schist as well as in other rocks. Diabase porphyrites often fill up a complex system of older and closely parallel shear planes and short joints connecting them, with less common isolated joints originating in the intrusion of a basic magma. The prevailing trend of these dikes is northeast, in conformity with that of the axes of the ore-field folds, and of the schistosity planes in crystalline schist. Dikes of other trends, northwesterly, latitudinal, meridional, and nearly meridional are also present. An orientation diagram for large fractures filled with dikes of the Aktyuz porphyrite and diabase porphyrite is zoned, with a polar belt of fractures of all trends but with

uniformly steep deep. There is a conspicuous high-centered maximum reflecting the predominance of steep northeasterly fractures.

## GEOLOGIC CONDITIONS OF FORMATION OF THE AKTYUZ FRACTURES

Fractures in crystalline schist. Two systems of related, nearly vertical fractures can be identified in the Aktyuz crystalline schist. The first is represented by meridional to latitudinal joints, diagonal to the fold axes and to the strike of the schistosity. The second system includes northwesterly transverse fractures and northeasterly bedding fractures.

As we have pointed out, the direction of displacement along the latitudinal and meridional fractures indicates that, at the time of their origin, the northeasterly and southwesterly quadrants were those of expansion, while the northwesterly and southeasterly were those of compression. Thus, the origin of a system of related, steep latitudinal and meridional joints was connected with the action of maximum tangential compression stresses acting from northwest to southeast. These stresses could have originated in a direct movement of the rock body, in that direction, or as the result of a torque. It is not impossible that they are derivatives of radial tectonic stresses.

This orientation of tectonic stresses is confirmed also by the axial trend of the ore-field folds and by steep longitudinal northeasterly shear faults. The origin of northwesterly vertical faults appears to have taken place, in part, simultaneously with the shearing. An oblique direction of the northwesterly tangential stresses (15 to 20° to the horizon) could have resulted in another system of shear surfaces. In that event, one of the directions of shear was determined by weakened steep schistosity surfaces, trending northeast, with the other direction determined by the counterdipping shear fractures.

The system of related steep shear fractures, trending northwest and northeast, was probably associated with a somewhat different orientation of tangential stresses. Judging from the direction of displacements, a submeridional northeasterly trend may be anticipated.

The causes of these changes in the orientation of tangential tectonic stresses are not clear. They may be related to a regional reorientation as well as to local changes in the field of force like those which occur in an intrusion of large bodies of magmatic melts, and to other causes. The second alternative appears to be the more acceptable.

Thus, there is every reason to believe that the origin of the bulk of fracture in crystalline schist of this ore field is related to tangential northwest-southeast stresses, while their submeridional orientation is of subordinate significance.

Fractures in columnar bodies and in the alaskite granite massif. The conditions of formation of fractures in the columnar bodies of the explosion vent type of this ore field, deserve particular attention. The formation of these bodies, and their subsequent development, are related to instantaneous upward forces. The latter originated in the pressure of magmatic melts and in recurrent gas explosions.

According to modern concepts of deformation of solid bodies, an instantaneous impulse deforms the latter as brittle bodies; even such plastic materials as tar undergo this type of deformation.

On the other hand, Ya. B. Friedman [8, 9] notes that brittle bodies are easiest and most often disintegrated by faulting. On the basis of these data, it may be assumed that, as the effect of instantaneous upward gas pressure, cylindrical, or nearly so, fault planes were formed in the crystalline schist of the ore field, along with radial fractures of the same type. Gases, breaking through them, fractured and turned to breccia the schist within these cylindrical surfaces. This probably accounts for the rounded horizontal sections, often shaped like a sickle or a horseshoe.

Subsequent gas explosions, associated with the intrusion of new magmatic melts into the already formed columnar bodies, brought about the local annular and semi-annular breccia zones, both within them and along their periphery and in the system of the above-mentioned faults and shearing fractures.

Because of a rapid removal of the load after the explosion, new fractures, of elastic rebound and gravity settling, could have originated in the columnar bodies. On the other hand, gravity displacement of a different sign could have taken place along the earlier fractures.

Sagging movements, and considerable ones at that (hundreds of meters), have been definitely established for columnar bodies in many parts of the world [1, 2, 10, 13-15]. In some places, they appear to be due to the outflow of magma. The amount of sagging in the Aktyuz columnar bodies appears to have been slight, from a few meters to a maximum of 15 m.

These considerations of the origin of systems of fractures in the Aktuyz ore fields have been substantiated by experiments on the deformation of rocks. According to Yu. A. Rozanov (oral communication), a cylindrical rock specimen under axial compression fails along a cone of crushing (Figure 10-a). Consequently, an

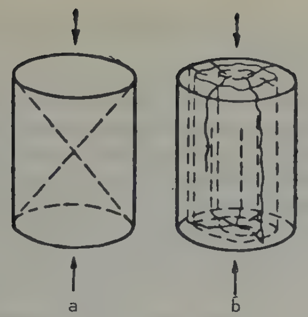


FIGURE 10. Experimental data on the deformation of solid bodies.

a - results of directional compression of a cylindrical rock sample; b - results of uniaxial compression of a rock cylinder with plastic pads on both ends.

infinite number of shear fractures originate — all tangential and dipping at about 45° to the axis.

When the end surfaces of a cylindrical specimen as well as the plunger surfaces are carefully polished or separated by plastic pads, e. g., of lead, the compressed specimen fails along cylindrical faults and along vertical radial fractures of the same type (Figure 10-b).

It is well known that stresses caused by reduction in volume originate in cooling-off igneous rocks. These stresses often result in more or less evenly distributed contraction fractures which break up the rock body into various blocks. This phenomenon is usually called the parting of igneous rocks; and fractures of this type are known as parting joints. Their best example is the polygonal and prismatic columnar parting in basalt flows.

No parting has been observed in igneous rocks of the Aktyuz columnar bodies. It appears that the origin of primary fractures was most affected by external forces of vertical pressure by a magmatic melt and its gas.

Fractures in the Aktyuz alaskite granite massif have much in common with faults in the columnar bodies: both are represented by variously oriented steeply dipping systems connected by gradual transitions. This is the explanation for the similar zoned structure of orientation diagrams for fractures in alaskite granite and in rocks filling the columnar bodies.

A difference between the systems of fractures in columnar bodies and in alaskite lies in their spatial distribution. While the first are characterized by annular and semi-annular distribution zones, this is not true for the second.

This similarity in the systems of fractures for columnar bodies and alaskite suggests that primary fractures in both were formed by vertical stresses, probably associated with the pressure of a magmatic melt in deeper horizons of the crust on the upper cooling surface of the massif.

As we have already noted, fractures in the Aktyuz columnar bodies are identical in orientation and regularity of distribution with those in the explosion vents of kimberlite, basic and ultrabasic rocks in carbonatite deposits, necks, batholiths, and any other similar igneous bodies. On the other hand, W. Emmons [11, 12] believes that many fractures in granite domes have been formed as the result of a break-through of magmatic gases [4]. The data cited suggest that conclusions on the conditions under which fractures in the Aktyuz columnar bodies and alaskite granites were formed have a broader meaning and are applicable to columnar bodies as well as to fracture intrusions and thick dikes in many other regions.

In igneous bodies of considerable areal extent but with rather narrow feeding channels, the chances for a transfer of vertical pressure upward through magmatic melts into deeper reaches of the crust are obviously limited. In such bodies, among them extrusive sheets, bedding sills, laccoliths, phacoliths, interformational bodies of a considerable areal extent, the formation of primary fractures is most probably affected the most by internal stresses related to the cooling and volume reduction.

Developed in columnar bodies and the alaskite granite of this ore field are not only the primary fractures formed under vertical stresses but also superimposed secondary fractures brought about by tangential stresses, as witness the many large fractures and minor latitudinal, northwesterly and other trends which cut and offset the alaskite and columnar bodies' contacts with crystalline schist.

Offsets in the column contacts by steep northwesterly faults can be seen in Figure 3. Present in the southwestern part of the ore field (Figure 1) are a considerable number of small sublatitudinal faults offsetting the alaskite contacts with green schist.

## SOME PROBLEMS IN THE HISTORY OF DEVELOPMENT OF THE FRACTURES

At least four orogenic epochs appear to have left their trace in the structure of the Aktyuz ore field: the Precambrian, Caledonian, Variscan, and Alpine.

Fractures in primary rocks, subsequently turned to crystalline schist, have been fully obliterated by subsequent processes of regional metamorphism and by plastic flow. The oldest faults superimposed on metamorphosed rocks

of this ore field apparently are associated with late stages of the Caledonian orogeny. This deformation was at its maximum during the Variscan orogeny, and partially during the Alpine.

The Variscan stage of formation of this ore field consisted of two essentially different phases, each characterized by tectonic conditions of its own. One is related to an intensive manifestation of tangential stresses; the other to their abatement, if not complete extinction. The growth and completion of earlier folds, as well as the beginning of their breaking up by normal and thrust faults along old and new faults and shear fractures occurred during the first phase; the second phase was a time of magmatic intrusions and of expulsion of their volatiles, resulting in explosion vents. Steep shear fractures of every trend opened in the crystalline schist, along with new and steep faults, mostly bedding faults, and less commonly of other trends, all accompanied by lateral displacement, while peculiarly oriented faults and shear fractures were formed in the cooling of igneous rocks.

The causes of such changes in tectonic conditions have not been worked out. First of all, it is not clear whether the second phase was the time of intrusion of magmatic melts; of the formation of primary fractures in igneous rocks; the opening of earlier fractures; and of other processes affected by tectonic stresses, acting radially downward; or was merely the result of reactive and some other forces. Specifically, the opening of steep fractures of any trend, as well as the formation of new faults, apparently could have been accomplished by reactive elastic and gravity stresses. Magmatic melts could have been intruded as a result of the vacuum, in the opening of steep fractures.

Belonging to late Variscan igneous rocks of the Aktyuz ore body are alaskite granites cut by fine-grained porphyritic varieties, early aplite and granophyre, dikes of porphyrite and diabase porphyrite, late granophyre, and dikes and irregular bodies of late aplite and syenite aplite. New shearing fractures, cutting and displacing the earlier igneous rocks, originated in the period between the formation of most of these rocks.

It appears from these data that no fewer than five tectonic changes took place in the late Variscan phase.

Primary fractures in igneous rocks of this ore field, having formed during the dying-down of tectonic forces, were rejuvenated in the period of their maximum manifestation; this time, the displacements along them were different than before, with a partial formation of new secondary tectonic fractures, superimposed on the primary ones.

In the period of abating tectonic forces, no substantial complication in the primary fracture systems took place, because that was a time chiefly of bedding faults. Exceptions are the zones of crystalline schist immediately adjoining the columnar bodies and the alaskite granite massif; especially those segments above the comparatively gently dipping contacts of upper parts of the columns. In such places, primary fractures in crystalline schist were complicated as a result of the recurrent gas explosions, by the emergence of new steeply dipping faults, and partly by patching up the primary fractures through biotitization of green amphibole schist (Figure 2a and 2b). A detailed study shows a wide development of biotitization in green schist along the fractures.

This consideration of the formation conditions for the Aktyuz fractures leads to certain general conclusions on the origin of fractures in igneous rocks. It appears that such fractures should be divided into two large genetically different groups, or primary and superimposed secondary fractures.

The primary fractures differ among themselves. In columnar igneous bodies, in stocks, fracture intrusions, and other morphologically similar bodies, primary fractures are formed as an effect of vertical stresses.

In bodies of considerable areal extent but with narrow feeding channels, such as extrusive sheets, bedding sills, lopoliths, interformational deposits, and other similar forms, the formation of primary fractures is related chiefly to internal stresses during the cooling-off period, and to volume reduction. Secondary, superimposed fractures were brought about by tangential tectonic stresses acting upon the igneous rocks.

In mobile crustal belts, igneous bodies are often affected by many orogenic phases, and occasionally by two or more orogenic epochs. Under such conditions, their primary fractures may be fully patched up or camouflaged by superimposed secondary fractures. In the Kara-Dzhilgin granite massif of the Kirghiz Range, we have observed such a complete patching up of primary fractures in zones of intensive schistosity and gneissitization of granite, and the appearance there of new systems of fractures quite similar to those observed in the enclosing crystalline schist. I. P. Kushnarev notes [5] that systems of fractures in Caledonian schistose quartz diorite, in one of the east Sayan ore regions, are quite similar to those in the enclosing sedimentary and metamorphic rocks. Platforms and shields have all the conditions necessary for the preservation of primary fractures in igneous rocks.

SUMMARY

1. Five systems of fractures have been identified in rocks of the Aktyuz ore field: steep fractures of northwesterly, northeasterly, latitudinal, and meridional trends, and a system of gently dipping, almost horizontal fractures. A great majority of these systems are connected by gradual transitions; consequently, most orientation diagrams for these fractures show a belt and a structure of their own.

2. Two types of diagrams and zonation have been differentiated by the orientation features. In the first, a warped polar zone of fractures bisects the diagram into two uneven parts. Such diagrams are typical of crystalline schist and related dike rocks.

Diagrams of the second type are marked by a polar zone of fractures with a uniformly steep dip but with the most diverse trends. In this type, the polar zone of fractures makes a circle along the diagram periphery. Such diagrams are typical of rocks in the columnar bodies; of the alaskite granite massif and of narrow bands of crystalline schist contacting the alaskite and the columnar bodies; and of some other rocks.

3. By far, most fractures which cut the crystalline schists have originated in the terminal period of folding, as a result of tangential stresses oriented chiefly northwest-southeast.

4. The bulk of the fractures in columnar bodies and in the alaskite granite massif were brought about by vertical stresses related to the pressure of magmatic melts and their gases on the crystallized upper part of the massif. As a result of subsequent tangential stresses, younger superimposed fractures were formed in the igneous rocks.

5. Conclusions on the conditions of formation for fractures in the Aktuyz columnar bodies and alaskite massif have broader implications and are applicable to columnar, stock-like, and similar igneous bodies as well as to fracture intrusions.

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# VITREOUS SPHERICAL LAVAS OF LEVAYA LEFU RIVER IN THE FAR EAST[1]

by

V. P. Petrov, and M. G. Zamurayeva

The extensive exploration for perlite minerals, which has been carried on in recent years in this country has contributed much to the petrography of vitreous rocks. This work has revealed many new deposits of volcanic glass and new forms of its occurrence. The Soviet Maritime Province has turned out to be quite an interesting area of vitreous rocks, with about ten newly discovered deposits, one of them, in the vicinity of Bogopol'ye, being commercial [2]. A complete description of all local glass deposits is not yet available because their outcrops are located mostly in dense forests and are poorly exposed.

Unfortunately, the Lefu deposit of basic volcanic glass has no commercial value, first because of its distance from means of transportation and second because of its low content of glass with a low expansion coefficient. However, the manner of occurrence of spherical lavas, along with the nature and distribution of glass in the lava flow and the structural details of the latter, are interesting enough to deserve a special study.

The Levaya Lefu deposit was discovered by a field exploration party headed by G. A. Lapshin, to whom we are grateful for having pointed it out to us.

## THE DEPOSIT

This deposit is located in the upper course of Levaya Lefu River (northern branch of the Lefu River), about 4 or 5 km above the village of Klenovka. Volcanic glass is associated here with a lava flow exposed in a steep cliff in the left bank, locally 50 to 70 m high and extending for over one km along the river. A thick forest prevented us from getting acquainted with the areal extent of the flow; however, the river cliff section has provided enough data, especially in its west end, sketched in Figure 1. Here, the base of the section is represented by porous well-crystallized basalt, apparently of an earlier flow. The overlying younger vitreous flow rests directly on the basalt. It is broken up into individual spheres, 0.5 to 1.0 m, seldom larger. Some spheres are quite regular; the others, as often occurs in spherical lavas, are somewhat elongated, warped, and loaf-like. As a rule, the lower spheres are more regular.

Space between the spheres is filled up by obsidian breccia of large (up to 1 to 3 cm) angular fragments of volcanic glass, and of a yellow groundmass of finely fragmented glass (average size of particles, 1.0 to 1.5 mm) with a film of iron-rich montmorillonite clay. This breccia is pierced by angular interfragmental pores. An estimate of its components cannot be accurate because it breaks up under a blow into a fine-grained yellow mass, thus giving the impression that the latter is the predominant component. A possibly more accurate estimate from large slides is as follows (in percent volume):

| | |
|---|---|
| Coarsely crushed glass | 50 |
| Finely crushed glass | 10 |
| Ferruginous clay | 25 |
| Pores | 15 |
| Total | 100 |

The breccia glass is fresh, without any evidence of crystallization. The boundary between the yellow intersphere mass and the spheres is quite sharp, with the spheres falling out readily. When split approximately along their diameter, many of the spheres show a more or less homogeneous structure. Figure 2 presents a photograph of one of these spheres, while Figure 3 is the sketch of a typical spherical structure. All zones indicated on the sketch are readily recognizable on the photograph.

The peripheral zone of spheres, in direct contact with the intersphere breccia, consists of streamlined volcanic glass. This streamline effect is expressed in minute fractures oriented roughly along the circumference (they outline the sphere), and in small bands of spherulites of an incipient crystallization oriented in the

[1]O steklovatykh sharovykh lavakh r. Levaya Lefu na dal'nem vostoke.

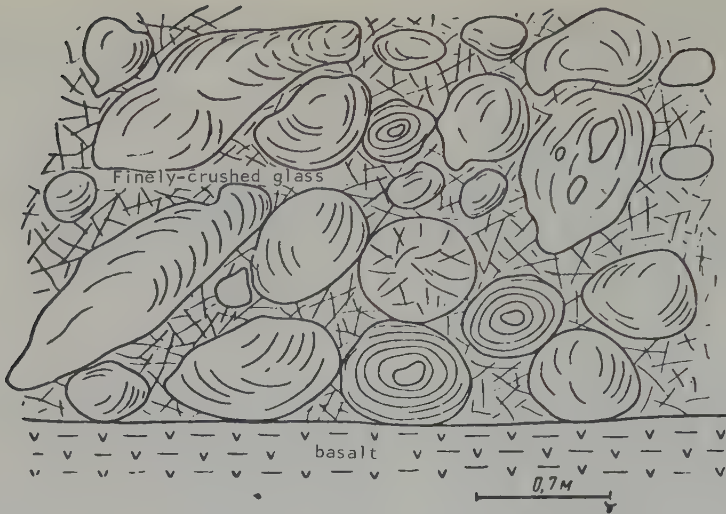


FIGURE 1. Diagrammatic sketch of part of the exposure on the left bank of Levaya Lefu River.

same way. The extent of crystallization increases toward the center, always maintaining a concentric arrangement; locally, the crystallization bands are broken up into small spherules with a dark interior and light-colored periphery (see Figure 4).

In a zone still nearer the center, massive glass is virtually missing, having been replaced by large spherulite. At the center of the sphere, these spherulites merge to form a fully crystallized body with barely discernible individual spherules. Finally, the center itself is occupied by a large pore of the miarolitic-cavity type, with its walls formed by the outer boundaries of spherulites. Besides the main central pore, some spheres contain marginal pores similar to it but considerably smaller.

## THE ROCKS

The glass in marginal parts of the flow and in the finely-crushed intersphere mass is, as a rule, quite clear; as seen under the microscope, it is yellow and isotropic in transmitted light.

Its composition, determined from sample 66, is given in Table 1 and corresponds

FIGURE 2. External view of one of the spheres at the base of the spherical lava flows.

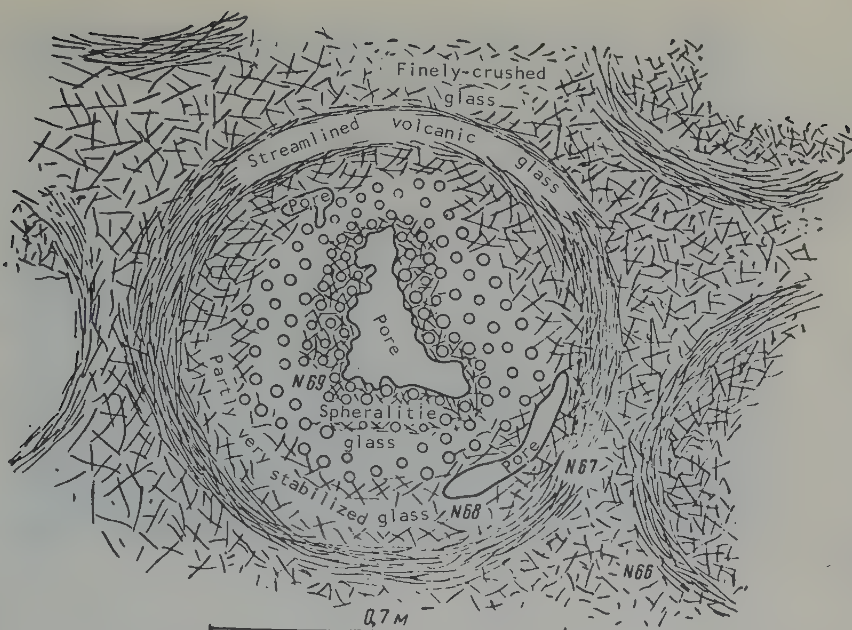


FIGURE 3. Structure of a sphere in the spherical lava flow. Numbers indicate the sampling places.

approximately to andesite-basalt. In order to present the possible results of the glass crystallization, this analysis should be converted to the mineral composition. That task, however, is extremely difficult because calcium may enter either pyroxene or feldspar in the process of crystallization; other oxides, too, may enter different minerals. Roughly, equal amounts of pyroxene and basic andesine will be obtained in complete crystallization, along with numerous iron-ore minerals.

Actual crystallization of glass during the cooling stage undoubtedly occurred in two phases. In the first phase, comparatively large, well-formed plagioclase and pyroxene crystals were precipitated; they are very rare in the glass, being present mostly in poorly crystallized segments of a sphere. The second phase is that of skeletal crystallization, finally leading to the formation of spherulites, and evidently following the first phase. Shown in Figure 5 is a glass segment where crystallization occurred

FIGURE 4. Structure of a sphere in the zone of partially crystallized glass; sample No. 68.

Table 1

Chemical analyses and mineral composition of glass (sample No. 66) and the crystallized segment of a sphere (sample No. 69) from the Levaya Lefu spherical lava flow (in %)

| Oxides | Sample No. 66 | Sample No. 69 |
|---|---|---|
| $SiO_2$ | 56.51 | 55.71 |
| $TiO_2$ | 0.92 | 1.24 |
| $Al_2O_3$ | 10.93 | 11.65 |
| $Fe_2O_3$ | 5.14 | 4.66 |
| FeO | 8.53 | 8.78 |
| MnO | 0.12 | 0.11 |
| CaO | 7.82 | 7.47 |
| MgO | 5.85 | 5.31 |
| $K_2O$ | 0.42 | 0.43 |
| $Na_2O$ | 2.92 | 3.06 |
| $-H_2O$ | 0.00 | 0.08 |
| $+H_2O$ | 0.00 | 0.31 |
| Loss on ign. | 0.93 | 0.96 |
| Total | 100.09 | 99.77 |
| Glass | 100 | 40 |
| Plagioclase | — | 40 (basic andesine) |
| Pyroxene | — | 20 (ferruginous) |

mostly in the first phase. Two pyroxene crystals of the diopside-augite series, and two crystals of andesine-labradorite plagioclase were formed as a result. This was the end of the pyroxene crystallization, while the plagioclase crystallization went on in skeletal form.

In that process, individual dendritic fibers growing over a plagioclase crystal have the same orientation, on the whole, as the inner crystal, thus forming a spherulitic aggregate. Skeletal crystallization is well illustrated in Figure 6 where the first generation crystal is located in the center of each spherule. Present among the skeletal rays are thicker fibers extending from the edges of this crystal, as well as a very fine mesh of minute branches of the principal rays. Along its periphery, the crystal changes to regular spherulite, Figure 7 presents the cross-section of a fully grown spherulite.

The composition of first-generation feldspar crystals is readily determined from their extinction angles ($\perp$ PM = 32°; labradorite No. 52). Determining the composition of the skeletal fibers is considerably more difficult. The only possible thing to do here is an immersion determination index of refraction; this is not highly accurate because of the dense intergrowth of feldspathic fibers and glass, and the impossibility of orienting the filament measured. Still, it was possible to determine with certainty that all fibers had a higher index of refraction than n = 1, 550 and lower than the n = 1, 570. These figures, as well as the extinction angles, correspond to basic andesine or to acid labradorite (No. 44-45).

Up to now, we have considered the formation of spherulites with reference to the feldspathic base, only. As a matter of fact, almost all spherules display two distinct zones (see Figure 4): a central, dark zone and a peripheral, light-colored zone. They are also seen in Figure 7. Both zones are similar in feldspathic minerals; the difference is that the dark zone contains exceedingly numerous, very fine pyroxene grains (of a few microns) among fibers

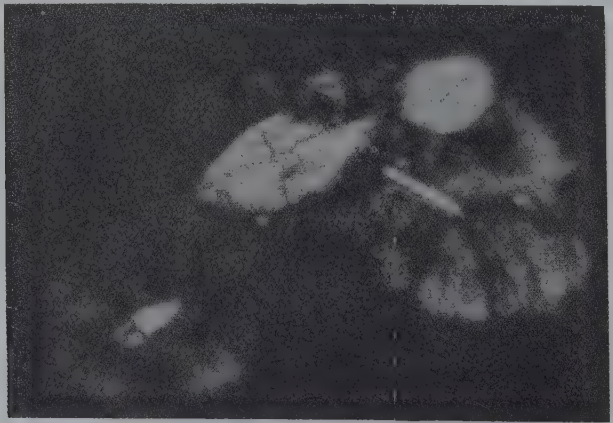

FIGURE 5. Two crystallization phases of volcanic glass: crystal incrustations and skeletal forms.

Nicols crossed. Magnification, 24 X.

FIGURE 6. A skeletal crystal of plagioclase "unfolding" into a feldspar spherulite.

Nicols crossed. Magnification, 36 X.

of the feldspathic skeleton. They are missing in the light-colored portion which is made up solely of feldspar and glass.

The crystallized part near the center consists of similar spherules, except that they are all dark, with the intersphere space fully crystallized. The same skeletal plagioclase and the minute pyroxene grains are present here, too; the plagioclase skeletons are oriented haphazardly, to form plumate to criss-cross shapes, depending on the section.

Only a tentative calculation of the quantitative mineral composition was possible for the crystallized portion; results are listed in Table 1, sample 69. The same sample was chemically analyzed, and the composition of the intersphere

FIGURE 7. Fully formed spherulite from the central part of a sphere.

Nicols crossed. Magnification, 36 X.

glass turned out to be practically the same as that of the crystallized rock.

Quite characteristically, no secondary minerals, formed after solidifcation of the glass have been observed in rocks within the spheres.

We shall turn now to the intersphere finely crushed glass (see microphotography in Figure 8). Its fragments consist of a uniform isotropic glass (light spots are anisotropic segments of glass, due to stresses and fractures originating in the preparation of the slide). The cementing mass is a porous aggregate of yellow montmorillonite clay with n = 1.487. This montmorillonite appears to have been formed by an alteration of volcanic glass, as witness the pseudomorphs of montmorillonite on glass, occasionally visible in slides (e.g., in the right side of Figure 8). As well as the formation of montmorillonite in fractures cutting the glass fragments (visible in a fragment at bottom of Figure 8).

## DISCUSSION OF THE RESULTS

The spherical structure of the Levaya Lefu andesite-basalt flow was formed on land. This is corroborated by the exceptionally slight alteration of glass, even in intersphere spaces, as well as by its poor crystallization (subaerial origin). The streamlined concentric bands suggest that the spheres were formed as the result of viscous rolling. That the fracturing took place in a viscous, not quite solidified glass, is suggested by the presence of finely crushed intersphere glass.

Quite significant is the presence of a central portion of the sphere, clearly a peculiar "settling shell", indicating that the sphere began to be formed while the glass was sufficiently hot. The rapidly cooled outer part of the sphere, the vitreous zone, made a strong envelope within which the glass shrank and crystallized.

It must be emphasized that the underlying basalt surface is flat and there are no "flattened" and "reniform" spheres at the base of the flow; most of them are perfectly rounded. Such a situation originated most likely in the rolling of the spheres over the basalt surface.

The existence of subaerial lava spheres was noted as early as the end of the last century [5] and confirmed subsequently by a number of volcanologists [6, 7]. This Levaya Lefu flow of spherical lava is one more example of that most interesting natural phenomenon.

By attempting to demonstrate a subaerial origin for the Levaya Lefu lava flow, we do not cast any doubt on the existence of subaqueous spherical lavas. The recent well-substantiated summary by M. A. Gilyarova [3] convincingly demonstrated several ways in which such lavas can be formed.

One of the authors had a chance to study definitely subaqueous spherical lavas in the Akal'tsikh region of the Caucasus [1]. The general aspect of those Caucasian lavas is quite different from that of the Far-Eastern lavas here described. In the Caucasus, lava in the interior of the spheres is much better crystallized, with the tempered outer parts

FIGURE 8. Intersphere breccia: black — glass; light color — montmorillonite clay.

In the large lower glass fragment, montmorillonite replaces the glass along a fracture. Nicols crossed. Magnification, 14 X.

strongly affected by hydrothermal activity. The entire outer zone, formerly glass, has turned to an essentially chlorite aggregate. In addition, secondary mineralization is well expressed in the Caucasian lavas, a deposition of zeolites and carbonates in intersphere cavities, and the presence here of limestone-like ooze.

Of significance is the very presence of intersphere cavities in the Caucasian subaqueous lavas and their lack in the Far-Eastern subaerial lavas, where there is instead the crushed glass breccia. The spheres themselves are considerably more oblate in the Caucasian lavas.

Another interesting fact observed in the Far-Eastern lavas is the relationship of the emerging crystal forms with the viscosity of magmatic melt. A liquid lava began to crystallize in a manner common to all lavas; then, as the glass became more viscous, its crystallization acquired a skeletal and spherulitic character typical of the devitrification of industrial glass.

A comparison of chemical compositions of massive fresh volcanic glass in peripheral parts of a sphere and the intersphere breccia, on one hand, and for crystallized rock in the center of the sphere, on the other, shows that no substantial changes occurred in the process of crystallization and cooling.

The field and petrographic work was done by V. P. Petrov; the chemical analyses, by M. G. Zamurayeva.

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# PALEOZOIC CONGLOMERATES IN THE NIKITINA RAVINE (MALAYA LABA RIVER, NORTH CAUCASUS)[1]

by

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## INTRODUCTION

The Nikitina Ravine metamorphic section has engaged the attention of students, on many occasions, by the form of its outcrops and their peculiar composition, setting it apart from all known Cambrian-Silurian and Devonian formations in the Peredovoy (Front) Range of the northwestern Caucasus. There are no published detailed descriptions of its physical composition, degree of metamorphism, and conditions of occurrence; nor is there a unity of opinion on its age. Different students assign it to Lower [1, 7] and Middle [4] Devonian; A. Sh. Kurbanov [5] believes that metamorphics of the Malaya Laba — Bol'shoy Zelenchuk area are Paleozoic but does not subdivide them any further.

We present to the reader new data of our own, on physical composition and occurrence of the Nikitina Ravine sequence and the underlying rocks, along with some conclusions on their origin and age.

Z. A. Sazonova participated in collecting and processing the material. Artificial concentrates (grindings) were studied by Ye. D. Nadezhdina. The work was done under the direction of G. D. Afanas'yev.

## I. GEOLOGIC STRUCTURE OF THE NIKITINA RAVINE

The Nikitina Ravine is a narrow and fairly gloomy canyon with steep, locally sheer, forested sides (Figure 1). Flowing in it is a small stream (right tributary of the upper Malaya Laba) which often turns, during spring rains, into a torrential cascade.

As observed by V. N. Robinson [7], "the most northwesterly Devonian outcrops occur in the Nikitina Ravine". "From here on, they extend in a 4 to 6 km wide belt, as far as the Bol'shaya Laba and cross it to the Gorelaya Ravine.

"Devonian rocks form a large longitudinal syncline here. In the southwest, they are in fault contact with lower Paleozoic outcrops, and locally with Middle Carboniferous deposits."

According to our observations, the Nikitina Ravine rocks form a syncline with a North Caucasian trend, and complicated by minor folds of a northwesterly, locally northeasterly, trend. The prevailing dip of the rocks is to the southeast, at 0 to 48°, less commonly up to 90°. Dips of the cleavage planes are 8 to 9° steeper than the bedding dips (Figure 2). There are vertical zones of crushing, up to 20 cm thick, trending N — 55 to 80° — W; also vertical faults trending S — 10° — E, which break up the rock body into blocks displaced relative to one another. According to G. D. Afanas'yev [1], and V. N. Robinson [7], Triassic deposits at the mouth of the ravine (for about 2.0 km) are underlain by a motley Permian sequence which, in turn, rests on metamorphics of the right bank of the ravine.

At the ravine's bottom, the Triassic is in fault contact with the metamorphic sequence. These rocks are cut by a quartz porphyry dike, up to 8.0 m thick. To the southwest, Mesozoic and upper Paleozoic beds of Mt. Golaya are underlain by Upper and Middle Carboniferous deposits; Lower Carboniferous (?) deposits rest unconformably on metamorphics of the left bank of the ravine.

A sheet of quartz porphyry rests almost horizontally, with but a slight westerly dip, directly on this sequence. Outcrops of similar rocks have been observed in the upper course of one of the tributaries of this ravine, as well as in the north of the ravine, between its two northeasterly tributaries.

For about 2 km downstream from the confluence of two northern tributaries, the base of the Nikitina Ravine metamorphics is made up of meta-shales (consolidated, pelitic, schistose formations) with clastic beds of various grain size: polymictic siltstone (1 to 3 cm thick), silty sandstone (2 to 50 cm), and sandstone (10 cm to 6 m). There are occasional

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[1] O paleozoyskikh konglomeratakh balki Nikitinoy (Severnyy Kavkaz, r. Malaya Laba).

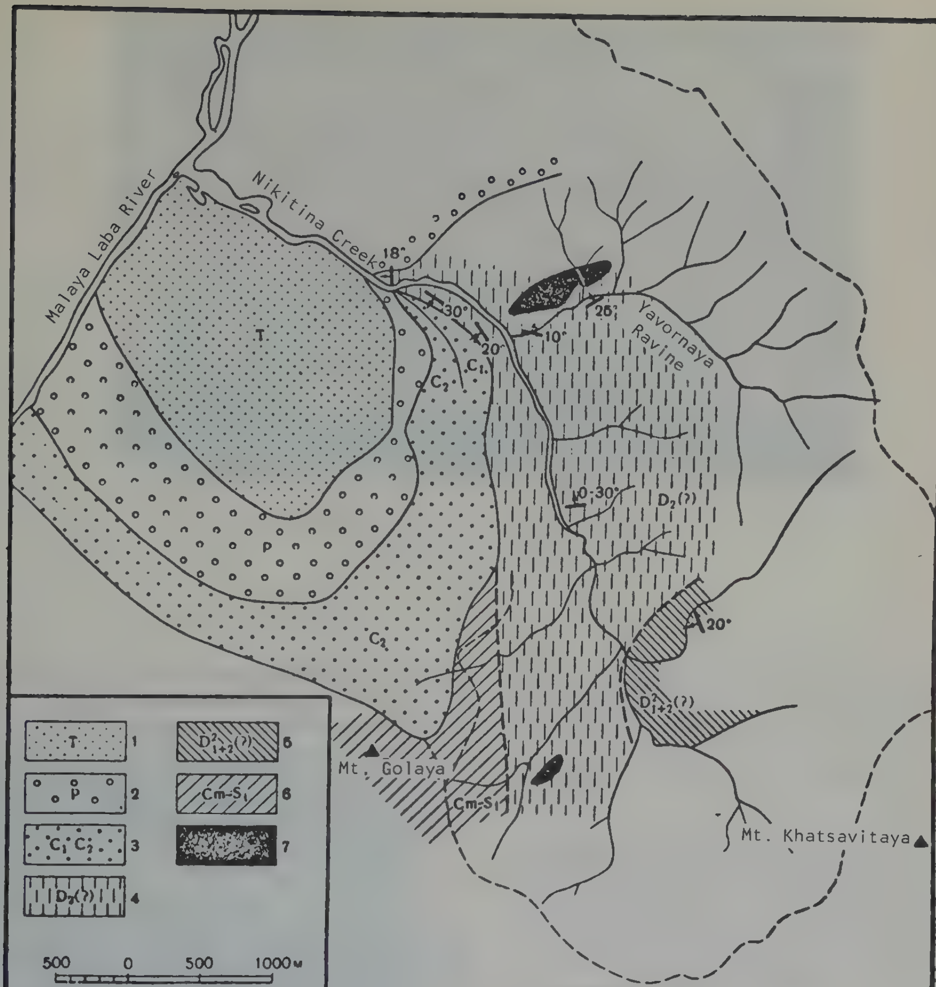


FIGURE 1. Geologic map of the Nikitina Ravine.

1 - Triassic; 2 - Permian motley section; 3 - Carboniferous; 4 - fluvio-glacial deposits of the Nikitina Ravine; 5 - southeastern fringe of the Nikitina Ravine; 6 - the Mt. Golaya rocks; 7 - quartz porphyry.

intercalations of quartz albitophyre tuffs. About 1.5 km up the ravine from the first metamorphic outcrops, the upper part of the Nikitina Ravine metamorphic section differs from its lower part by numerous conglomerate outcrops.

Conglomerates form small isolated hillocks, up to 10 m high and over, widening at the base to tens of meters and narrowing at the crest to a few meters, with steep, almost vertical slopes. They are located at various topographic elevations. Their internal structure is well exposed in longitudinal sections along the Yavornaya Ravine and in transverse sections along the Nikitina Ravine.

The conglomerates are made up of thick-bedded coarsely clastic gravel and sandstone (Figure 3), with ill-sorted pebbles (from a few centimeters to 0.5 m), unevenly stratified and well rounded but of various shapes — round, flattened, ellipsoidal, flat-iron shaped (Figure 4) — and carrying numerous boulders.

Locally the gravel bodies are covered by sandstone, 10 to 20 cm thick, and are cut by "veins" (up to 3 m thick; Figure 5) with "branches" (from a few to tens of centimeters thick) and intercalations of meta-shales (up to tens of centimeters thick). These conglomerate hillocks are grouped into a northeasterly ridge, 1.5 km wide and several kilometers long. They are spaced closer to each other in the lower, the northern course of the Nikitina Ravine, and farther apart in southern outcrops.

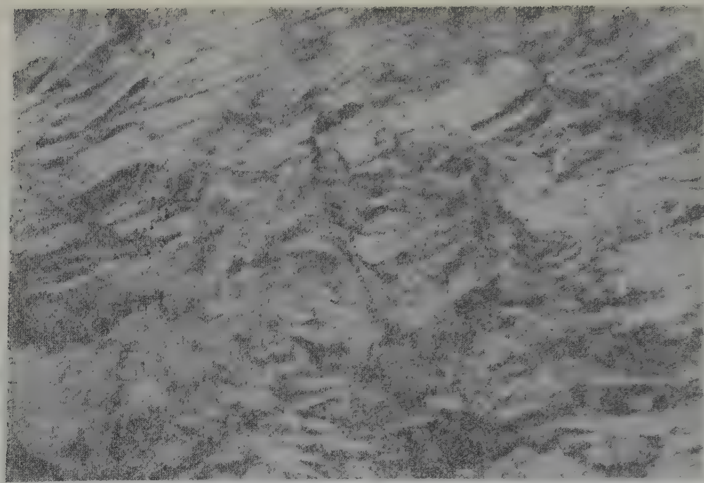

FIGURE 2. Outcrops of meta-shales.

Phot. by V.I. Gryazeva

The conglomerates are surrounded by meta-shales with intercalations of polymictic coarse sandstones, gravel beds (from 10 cm to 6 m thick), and accumulations of well-rounded pebbles (from 10 to several tens of centimeters thick).

Conglomerates in hillocks and intercalations are ill-sorted and diversified in the composition of fragments and pebbles. The presence of rounded chromite fragments indicates an erosion of ultrabasic rocks, while garnet pebbles indicate the erosion of crystalline schist.

Most common are the pebbles of intrusive, sub-intrusive, and extrusive acid rocks. The source rocks of these pebbles and fragments are exposed in the area of the Bol'shaya Laba, Urup, Beskes, Bol'shoy Zelenchuk, Teberda, and Kuban Rivers; they also underlie the Nikitina Ravine formation whose total thickness is about 100 to 150 m.

The northeastern and south slopes of Mt. Golaya, which is in fault contact with the ravine deposits, are made up of the Malaya Laba lower metamorphic formation ($Ca - S_1$):

FIGURE 3. Conglomerate outcrops.

Phot. by A.A. Semichastnyy

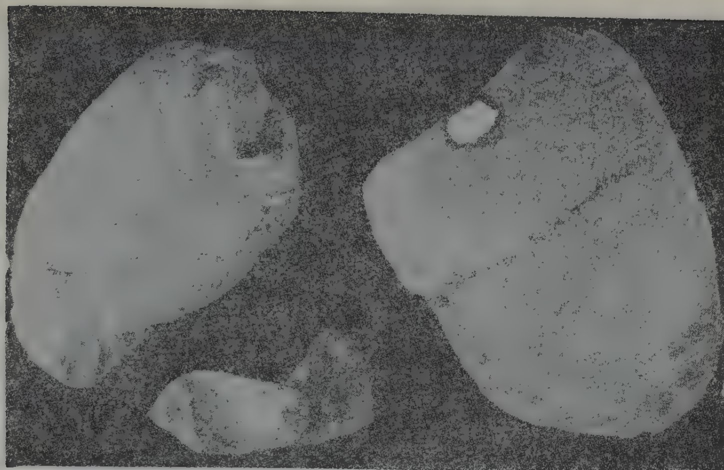

FIGURE 4. Conglomerate pebbles.

1/2 natural size

FIGURE 5. Outcrops of conglomerate with sandstone stringers (P)

Phot. by V.I. Gryazeva

epidote-actinolite and epidote-chlorite schists (completely altered basic porphyrite), and metamorphosed basic to intermediate porphyrite and tuff.

Present in the southwestern slope of Mt. Khatsavitaya are quartz albitophyre and tuff, chlorite schist, and phyllite. Exposed to the southeast are strongly metamorphosed paraschists of sandstone, siltstone, and pelites, altered to epidote-chlorite-pumpellyite schist with variable amounts of rock-forming minerals (epidote and pumpellyite), interbedded with flows and tuffs of quartz plagioclase porphyrite, with a dike (up to 4 m thick) of basic porphyrite (uralitized pyroxene-plagioclase). At the porphyrite contact, the phyllite and siltstone are lighter colored, having been altered to chlorite-mica schist. No direct contacts of this formation with the Nikitina Ravine metamorphics under which it dips have been observed.

## II. PETROGRAPHIC DESCRIPTION OF ROCKS

### 1. Meta-shale, Polymictic Siltstone, Silty Sandstone, and Sandstone

Meta-shale consists of black fine-grained, finely slaty varieties, with a greasy luster on cleavage surfaces, readily broken into small slabs. Thin stratification, not coinciding with the cleavage, is noticeable on breaks. Weathered slates are covered by a rusty bloom of iron hydroxide.

Microscopic study reveals a stratified structure (Figure 6), with a dark fine-grained (fragment diameters of about 0.01 mm) rock containing lighter-colored laminae (up to 4.5 mm thick) enriched with silt fragments.

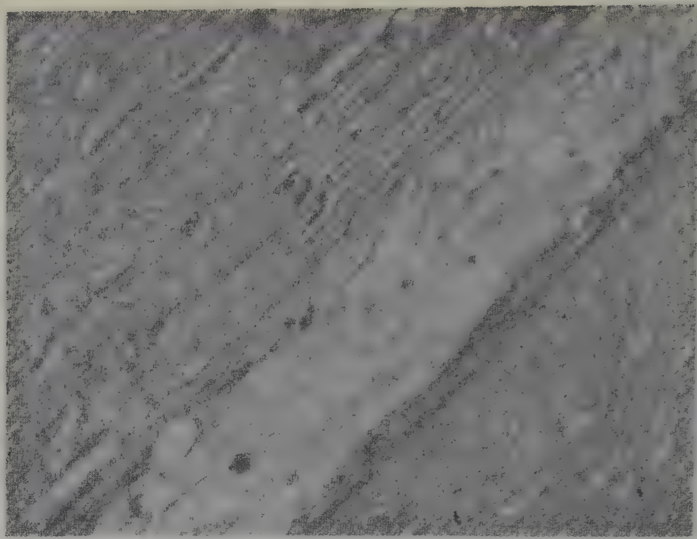

FIGURE 6. Meta-shales.

Specimen 476; magnification 27 X; single Nicol

The silts are light to dark gray, massive, with fragment diameters of 0.01 to 0.1 mm, less commonly 0.4 mm.

The silty sandstone (Figure 7) is usually non-stratified, with a conchoidal break, dark gray with a purple cast. Thicker beds are locally finely stratified. The fragments are 0.03 to 0.5 mm, seldom up to 1.0 mm.

The sandstone is medium-grained, massive, with a rather inconspicuous schistosity. Its grain size is 0.01 to 4.1 mm, commonly 0.1 to 1.5 mm. Locally present are rounded pebbles (1 to 5 mm, less commonly 10 mm) and fragments (up to 3 mm) of pink to light-green epidote, arranged parallel to stratification.

The coarse-grained sandstone and gravel beds (Figure 8) are gray, medium-grained, schistose rocks with an inconspicuous stratification. Noticeable to the naked eye are occasional fragments and flattened round pebbles, 2.7 x 0.9 to 3.2 x 1.4 mm in cross-section, with smaller grains 0.5 to 0.7 mm in diameter. All these fragments are of the same form and composition.

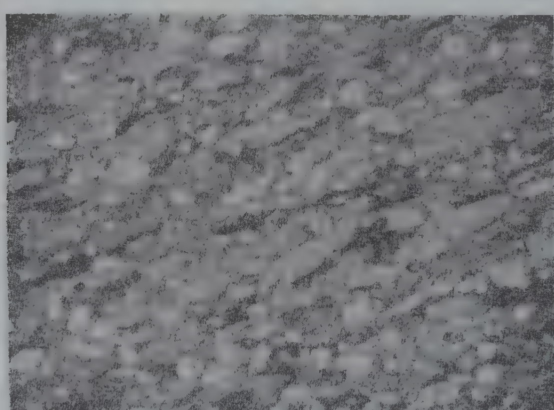

FIGURE 7. Silty sandstone.

Speciman 173; magnification 8 X; single Nicol.

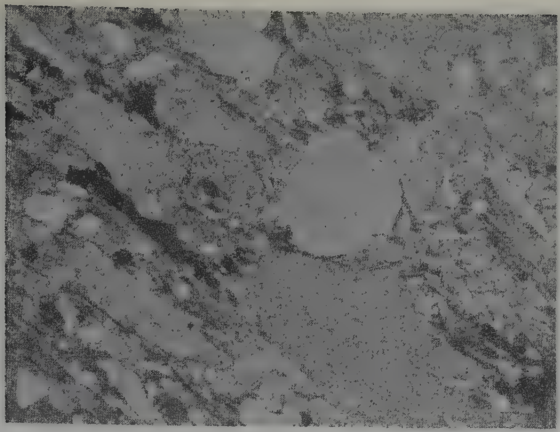

FIGURE 8. Gravel bed.

Specimen 459; magnification 8 X; single Nicol

The fragments (angular, semiangular, less commonly semirounded and rounded) are represented by cataclastic quartz, with wavy-extinction; plagioclases — Nos. 9, 17, and albite; colorless to yellow (ferruginous) epidote, light-colored actinolite; leucoxene; sphene in transparent, flat, bright- to lemon-yellow (in meta-shale) and copper-yellow envelope-like to flat crystals with occasional dark inclusions of ore minerals or graphite (?), grain diameter up to 0.45 mm (in sandstone); and rounded chalcedony fragments (in meta-shale). Occurring in smaller amounts, often in isolated grains (in grindings), are fragments of dark-green hornblende, muscovite, greenish-brown (in meta-shale) to brown and drab-brown (in sandstone) biotite, 0.5 mm diameter; carbonates; barite; transparent pink garnet (crystals without evidence of corrosion, in sandstone); apatite in crystals and rounded grains with frosted surfaces (in sandstone); red-brown prismatic rutile; and zircon of two varieties: one variety prominent in all rocks; the second, only in sandstone.

The first variety zircon is present in elongated prismatic, well-rounded grains (combination of two prisms and two pyramids), 0.20 to 0.56 mm diameter, without any evidence of corrosion; the grains are light-colored, slightly pinkish (in meta-shale and sandstone) to brown, orange, in places gray-brown, with step-like growth zones (in sandstone), occasionally with slightly rounded angles. The second variety is represented by short columnar grains, gray-white, clouded and opaque, with a greasy luster on faces. Both varieties of zircon contain bubbles of gas and fluid.

Chromite is present in sandstone, in octahedrons (up to 0.75 mm) with unevenly preserved faces; some of the grains are fresh, rounded, with rounded angles. In addition, the sandstone carries coarse collomorphic spherules (reniform to nodular), typical of sedimentary pyrite.

Graphite (?) has been observed in sizable amounts in all varieties of finely clastic rocks.

Present in silty sandstone are fragments of micropegmatite, growths of quartz and chlorite, a ground mass of albitophyre, and growths of pumpellyite; the sandstone contains fragments of quartz-sericite (?) and quartz-chlorite and chlorite schist, albitophyre, quartzite, spilite, plagioclase-quartz growths (granodiorite fragments), and sandstone with a sericite cement.

The groundmass of meta-shale is fine-grained, often crustified. The cement in silt, silty sandstone, and sandstone is most often massive, less commonly crustified (fine alternating individuals of quartz and chlorite, growing normal to the fragment surfaces); also regeneration (growth of quartz fringes) and corrosion cement (at the fragments' edges, plagioclase is corroded and replaced by chlorite), as well as cement in clots. The last two cement types have been observed only in silty sandstone. Spectrograms of meta-shale have revealed, besides the rock-forming elements (Si, Fe, Al, Mg, Ca, Na, Mn), the presence of Pb, Zr — 0.004 to 0.006%; Ga, Co, Ni — 0.001 to 0.003%; V, Zn, Sr — 0.01 to 0.03%; Cu — 0.001 to 0.006%; Ti — 0.1 to 0.3%; Cr — 0.004 to .03%; Ba — 0.004 to 0.009%.

Pb, Zn, Cr, Zr form individual minerals (galena, sphalerite, chromite, and zircon); Co, Ni, and Cu are present probably as additions in pyrite; V and Ti in magnetite and ilmenite; Ba and Sr in barite; and Ga in colored minerals.

Spectrograms of non-electromagnetic fractions of meta-shale and sandstone, enriched in pyrite with an addition of zircon, galena, rutile, sphene, apatite, epidote, and barite, revealed higher contents of Cu and Co — 0.04 to 0.06%; Ni — 0.01 to 0.03%; Zn — 0.04 to 0.6%; Sn — 0.007 to 0.009%; Pb — 0.1%; and small amounts of Ag — 0.0001 to 0.0003% and As — 0.01 to 0.03%.

## 2. Coarse-Grained Polymictic Sandstone and Gravel Beds

The coarse-clastic varieties are made up of poorly sorted, angular, less commonly rounded to warped fragments of rocks (1.0 to 5.0 mm and over) and minerals (0.1 to 2.5 mm). The mineral fragments are similar to those described above, with an addition of isolated grains of monazite, orthite and sphalerite (in growth with galena), crinoids (Figure 9; a non-index form), epidosite and quartzite (secondary?); and of a silicified rock with sulfides and "expansion areas" of quartz and chlorite (Figure 10). The cement is stratified, commonly schistose and clastic, with individual segments enriched in chlorite, carbonate, and micaceous minerals, the amount of which is considerable in some rocks, with mica flakes bent about the fragments.

## 3. Conglomerate

The conglomerates are made up mostly of isolated angular to semirounded and well-rounded pebbles, commonly flattened, oval, ellipsoidal, and flat-iron shaped, from a few centimeters to 15 x 20 x 27 cm and up to 55 cm along the major axis. Acid varieties predominate in the fragments and pebbles: plagiogranite, plagiogranite porphyry, and aplite (of the Urushten complex); plagiogranite and plagiogranite prophyry with biotite; albitophyre and quartz albitophyre of subintrusive and extrusive origin; also less common diabase spilite, mandelsteins, basic and acid feldspar porphyrite and tuffs, epidote-chlorite para- (limestone) and ortho-schists (porphyrite), epidosite, quartzite, siltstone, and limestone. Their cement is coarsely clastic with intercalations of sandstone, siltstone, and meta-shale.

Present in all of these rocks are veinlets of quartz, white to pink carbonate, and carbonate with quartz and iron hydroxide.

Present in conglomerate pebbles are the following rocks (the largest and acid-rock pebbles are most common):

a) Plagiogranite, plagiogranite porphyry, and aplite (Urushten complex). Macroscopically, the Urushten plagiogranite is medium-grained and leucocratic; standing out on a light background of plagioclase and quartz grains are fine (up to 1 mm across) chlorite tablets and isolated grains of an oxidized ore mineral.

Microscopically, these varieties have a hypidiomorphic texture produced by widely prismatic xenomorphic to semi-idiomorphic,

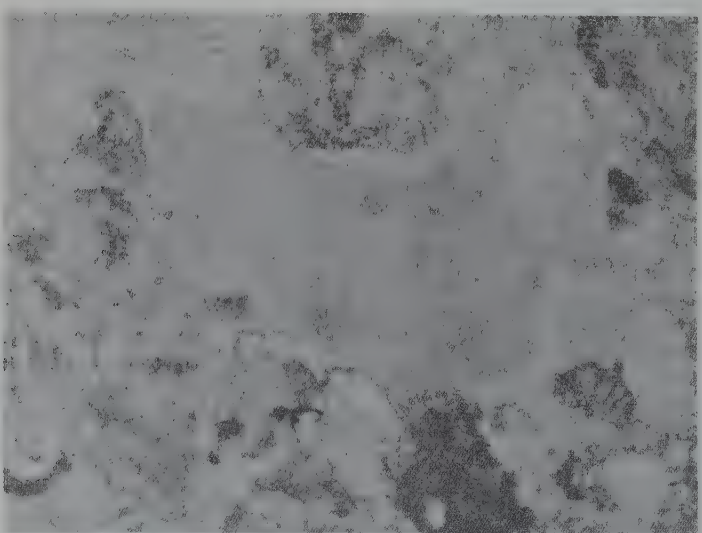

FIGURE 9. Gravel bed.

Crinoid fragment; sample 487; magnified 27 X; single Nicol.


FIGURE 10. Metamorphic schist with sulfides and "expansion areas" of quartz (Q) and chlorite (Ch)

Specimen 476; magnification, 9 X; single Nicol.

polysynthetically twinned grains of No. 12-13 brownish plagioclase, clouded by alteration products (sericite, epidote, carbonate), and often with a sieve-like texture brought about by growths of quartz. Often the periphery of the grains, and at times the entire grains, are fully replaced by a checkerboard albite.

The xenomorphic cataclastic quartz grains are rounded, also occurring in pegmatitic growths with plagioclase along the periphery of its grains, and giving the impression of a later silicification of the rock. Secondary and accessory rocks are represented by occasional epidote grains, indigo-blue chlorite, leucoxene (in chlorite), and rare apatite and sphene. The fractures are filled with carbonate and chlorite.

Macroscopically, the Urushten plagioclase consists of light-gray, fine-grained varieties; microscopically, they are somewhat porphyritic. Larger grains of plagioclase No. 5-6 and mylonitized quartz stand out against a fine-grained background of the same minerals. There are occasional grains of strongly pleochroic red-brown orthite with wavy, corroded outlines; and of apatite. Growths of chlorite and sphene, locally brownish, pleochroic, are fairly common surrounding the ore minerals. Also present are grains of oxidized sulfides and epidote.

It is possible that the sulfides and epidote are of a later origin, related to the formation of veins of carbonate, chlorite, and epidote.

The plagiogranite porphyry is similar in composition to aplite, differing from the latter only in size of inclusions and of groundmass mineral grains.

b) Plagiogranite with biotite. Macroscopically, the plagiogranite of this group is a dark-gray, fine-grained, somewhat gneissoid rock with assorted grains of a dull-gray plagioclase, white quartz, dark-green chlorite, and yellow epidote.

Microscopically, these rocks are characterized by the presence of plagioclase idiomorphs and of brown biotite.

Idiomorphic grains (up to 4 x 3 mm across) of polysynthetically twinned plagioclase are zoned and completely altered, as a rule, with larger epidote grains in the center; and finer-grained individuals with sericite, along the periphery. In some segments, plagioclase has been partly altered, with some grains sericitized and the others replaced by checkerboard albite. The plagioclase is albitized (albite No. 5-6). Xenomorphic quartz grains carry gas or fluid inclusions and fill up the interstices in the idiomorphic plagioclase.

Colored minerals are represented by brown, strongly chloritized and epidotized leucoxenic biotite. Chlorite contains idiomorphic (simple twins) grains of albite No. 6; idiomorphic apatite; monazite with haloes; a black, transparent dark-red, radioactive mineral (not identified) surrounded by haloes; and idiomorphic, apparently titaniferous magnetite, replaced by slightly talcose chlorite, with a leucoxene mesh.

Occasionally present are xenomorphic brownish grains of Na-orthoclase with the following optical constants:

Table 1

| Sample No. | 2V | P | | |
|---|---|---|---|---|
| | | Ng | Nm | Np |
| 193-a | —86° | 90° | 18° | 74° |
| | | M | | |
| | | Ng | Nm | Np |
| 193-a | —84 | 88 | 90 | 4 |
| 156 | —85 | 90 | 80 | 14 |
| 156 | —86 | 83 | 83 | 9 |

Some varieties are strongly carbonatized; the others are sericitized and mylonitized, with the fractures filled by quartz, chlorite, and carbonate with ore grains.

The plagiogranite porphyry is a structural variety of this group of granitoids, differing from the other granitoids in the size of inclusions and groundmass grains. The groundmass locally contains micropegmatite and pseudospherulites of radial quartz and plagioclase or quartz-epidote growths; its texture locally is micropoikilitic to hypidiomorphogranular. Also present are sphene and apatite.

In the nature of plagioclase isomorphism and the texture of the groundmass, these granitoids are somewhat reminiscent of the Bol'shoy Zelenchuk area plagiogranite.

Present in the granitoid pebbles are carbonate-quartz veinlets (up to several centimeters thick) whose ends appear to be "squeezed" in the cement about them. Occurring in these veinlets are accessory galena, sphalerite, pyrite, apatite, zircon (light-colored, brown to pink), and red-brown semitransparent rutile (?) in small prismatic crystals. The Nikitina Ravine sedimentary section is cut by many quartz veins with grains of brown sphalerite and pyrite; also by carbonate-quartz veins with apatite, tourmaline, native lead, ilmenite, pyrite, chalcopyrite, malachite, and azurite.

c) Albitophyres and quartz-albitophyres (subintrusive and extrusive). Macroscopically, these are well-rounded pebbles (a few tens of centimeters in diameter) of subintrusive albitophyre, dark gray to green gray, in places with a light-gray weathered zone. On a break, these rocks are fine-grained, slightly schistose, with plagioclase incrustations (up to 1 or 2 mm across).

Microscopically, they exhibit a variety of porphyritic textures. In incrustations are polysynthetically twinned plagioclase grains, replaced by carbonate, chlorite, and sericite. The plagioclase is albitic in composition.

The groundmass is prismatically granular, verging on hypidiomorphic, locally micropoiilitic, but felsitic in finer-grained rocks, in places with spherulites of fine-grained radial growths, apparently albite and quartz, of serrated outlines (up to 0. 18 x 0. 04 mm); also albite grains immersed in an aggregate of xenomorphic quartz grains with an addition of chlorite, carbonate, and occasionally epidote.

Present among accessory minerals are idiomorphic brownish apatite; brown pelochroic sphene, in places with an ore-mineral fringe; accumulations of leucoxene, probably on ilmenite; and pyrite. Extrusive albitophyres in well-rounded pebbles (1 x 2. 5 x 4 cm and larger) are lighter in color than the hypabyssal rocks; they are aphanitic, free of inclusions, and commonly show a conchoidal break.

Microscopically, these are porphyritic rocks with inclusions (0. 1 x 0. 3 to 0. 4 x 1. 6 mm across) of clouded brownish albite No. 8. 5, idiomorphic, polysynthetically twinned, occasionally consisting of several intergrown grains, with sericite, chlorite, and saussurite. The groundmass is streamlined, felsitic, made up of extremely fine albite grains, quartz, and chlorite fibers. Radial epidote is present locally. Accessory minerals are the same as in the above-described variety of albitophyre.

Also present are strongly schistose, quartzitic rocks, locally with sericite and carbonate along the planes of schistosity. Some varieties carry grains of iron sulfides with "expansion areas" of quartz.

The latter variety probably belongs to the lower series of metamorphic schists (Cm - $S_1$), while the fresher varieties are quite similar to the Urup area rocks (younger ?) assigned to the Middle Devonian by geologists of the Urup Exploration Party [9].

Quartz albitophyre of the intrusive and subintrusive bodies differ from those described above only by the presence of inclusions of a wavy-extinction quartz, often with gas and fluid bubbles.

All of these rocks carry veins of quartz and carbonate. Described below are pebbles of less common varieties.

d) Diabase spilite shows a diabase texture, microscopically. The idiomorphic, polysynthetically twinned grains of plagioclase-albite are commonly warped and carry very fine fibers of actinolite and grains of epidote. There are occasional coarser epidote grains, probably formed out of the plagioclase inclusions. The interstices are filled with chlorite, carrying fibers of greenish actinolite, also with grains of epidote and accumulations of leucoxene (on ilmenite) and hematite.

This rock is strongly silicified (wavy extinction quartz), similar to the Urup diabase spilite (Middle Devonian ?, [9]). A well rounded fragment (5. 5 x 3. 2 mm) of strongly altered quartzitic diabase spilite with accumulations of epidote and grains of sulfide showing "expansion areas" of quartz and chlorite was observed in gravel beds (specimen 47-c). This rock apparently belongs to the lower metamorphic sequence (Cm - $S_1$).

e) Porphyritoid. Macroscopically, this is a green-gray, finely schistose rock with yellowish grains (1 x 3 mm) parallel to the schistosity. Under the microscope, the porphyrite is seen to consist of angular prismatic plagioclase grains aligned with the schistosity and fully altered to and replaced by a colorless mica (?), locally with chlorite, quartz, and epidote. The groundmass is fine-grained, made up of chlorite, zoicite, colorless mica (?), altered plagioclase, rare apatite prisms, and numerous grains of sphene, leucoxene, pyrite, and iron hydroxide. The rock is silicified and carbonatized.

f) Metamorphosed basic porphyrite. Macroscopically, this is a black, finely schistose variety. Macroscopically, it is a very strongly altered rock whose porphyritic texture is barely discernible with crossed Nicols. Its plagioclase is made up of idiomorphic grains (1. 8 x 0. 5 mm) fully replaced by albite, chlorite, and carbonate. There are occasional incrustations (0. 7 x 3. 0 mm) of a chlorite-leucoxene aggregate, probably on a wholly altered colored mineral. The groundmass is fine-grained, made up of chlorite with numerous sericite (talc ?) scales. There are numerous idiomorphic apatite grains along with accumulations of leucoxene and some prismatic radioactive mineral, showing no extinction under crossed Nicols because of an accumulation of exceedingly fine colorless scales; also a bright red to yellow, isotropic to slightly anisotropic mineral (uranium ochre ?). Both minerals are surrounded by pleochroic haloes. The second mineral also occurs near the walls of chlorite- and carbonate-quartz veins. Also present are numerous idiomorphic grains (0. 08 x 0. 06 mm) of pink-brown pleochroic apatite, apparently secondary (one of its crystals containing a rounded crumb of the rock groundmass).

This rock (specimen 461) is free of the secondary brownish apatite but carries considerably more of the colorless primary variety, along with grains and grain aggregates of pyrite with chlorite "expansion areas". The radioactive mineral is represented by an early variety. Macroscopically, rounded grains (1 x 7 mm) are seen to parallel the schistosity, on a dark gray-green background. Grains of zircon and quartzitic pleochroic sphene have been observed in specimen 462. These rocks are silicified.

g) Basic mandelstein is present in angular fragments (5. 9 x 4. 6 mm) of amygdaloidal rock with incrustations (0. 55 x 0. 2 mm) of polysynthetically twinned plagioclase No. 6 with an addition of saussurite, sericite, and chlorite. The groundmass is fine-grained, consisting of very fine leucocratic grains of plagioclase (?), also chlorite, accumulations of leucoxene and sericite (talc ?), and a fine ore dust. Rounded pores (0. 1 to 0. 5 mm in diameter) are filled with chlorite and a wavy-extinction quartz. Quartz and carbonate are present in microfractures.

h) Tuffs of an intermediate composition are clastic rocks made up of oval plagioclase fragments (diameter of about 30 mm) arranged parallel to the schistosity; the plagioclase is warped, with a wavy extinction, strongly altered and replaced by albite, zoisite, sericite, and carbonate. Also present is mandelstein with a semi-transparent chlorite groundmass with prisms of zoisite and rare plagioclase microlites. Numerous oval and rounded vugs are filled by chlorite with fringes of non-transparent leucoxene (?) and occasional quartz. This rock is similar to intermediate plagioclase porphyry occurring in the southeast of the Nikitina Ravine.

i) Epidote-chlorite schist is represented by two varieties: the first was formed of fully altered intermediate extrusives; the second, of metamorphosed limestones.

The first variety is a porphyritic, strongly quartzitic rock with rare relict polysynthetically twinned plagioclase incrustations (0. 5 to 1. 0 mm), altered and replaced by chlorite, epidote, and sericite; in addition, less common cataclastic quartz and aggregates of epidote grains which have replaced the plagioclase. The groundmass is finely schistose, made up of chlorite with a sieve-like structure of quartz growths, numerous epidote grains, aggregates of leucoxene, and rare tablets of sphene. The second variety is a dark gray-green schistose rock with white carbonate spots (up to 1 cm long) aligned parallel to the schistosity.

Microscopically, the schist is made up of chlorite aligned with the schistosity; of numerous grains of slightly brownish to lemon-yellow epidote, locally zoned (in grains and aggregates);

and of hematite. There are relict segments of serrated grains and groups of grains of polysynthetically twinned, warped, strongly dolomitized calcite with magnetite pockets. Aggregates of fine epidote and chlorite grains have been observed in fissures in the carbonate. The rock is strongly quartzitic.

j) Dolomitic limestone, gray, massive, fine-grained rocks of two types, were represented by six well-rounded ellipsoidal to flattened pebbles, 5 x 5 x 3 cm to 10 x 10 x 20 cm. The first and most common type is a schistose, uneven-grained, marble-like limestone. It contains relicts of polysynthetically twinned, serrated, and locally warped grains (0.5 x 1.5 mm) of slightly dolomitic calcite in a fine-grained (0.01 to 0.1 mm) aggregate of xenomorphic calcite grains, also partly dolomitic and locally fully so, and commonly elongated parallel to the schistosity.

There are ovoid to oval xenomorphic grains (0.2 to 1.0 mm) of brownish magnesite (?), probably relicts of microfossils; also rare fragments (0.02 to 0.1 mm across) of polysynthetically twinned plagioclase, quartz grains, and veins of dolomitic calcite. These rocks are locally highly silicified along the schistosity.

The second type of limestone, not as common, is marked by a nodular structure. The nodules consist of fine dolomite grains standing out against a background of calcite grains. The limestone dolomitization is uneven, with some segments more altered than others.

Spectrographic analyses of dolomitic limestones from five pebbles are presented in Table 2 which also lists, for comparison, the results of spectrographic analyses for similar rocks from the Bol'shoy Ptsitser and Turovaya Bashnya (Dzhentu Range) mountains, the Blyb River area, and from a Triassic limestone at the Dzhentu Range pass. This table shows that dolomitic limestones of these pebbles carry Mg, Sr, Ba, Fe, and Mn, present probably in carbonates; the remaining additional elements (Si, Ti, Al, Na, Pb) come from plagioclase and quartz; Ca, V, Ag, Zr, and Cr are not always present, probably being the components of accessory minerals.

In chemical composition, additional elements, and nature of metamorphism, dolomitic limestones represented by these pebbles are very similar to those from the Dzhentu Range, Mt. Bol'shoy Ptsitser, and Blyb River, believed to be Middle Cambrian, by V. N. Robinson [3], and middle Paleozoic, i.e., Lower Silurian, by Yu. D. Bochkov [2], on the basis of new faunal findings.

It is not impossible that dolomitic marble $D^2_{1+2}$(?) had been affected by glacial erosion; this rock was not encountered in outcrops, but a large block was found in the channel of one of the upper right tributaries of Nikitina Ravine.

#### 4. Quartz Albitophyre Tuffs

These are coarse clastic rocks (diameter of fragments, 0.6 to 2.7 mm) made up of angular fragments of quartz, albite No. 9, a basic fine-grained to felsitic and microlitic groundmass, and fragments of quartz albitophyre itself; also present are tablets of chloritized biotite.

The cement is finely clastic, made up of fragments (0.1 mm) of the same composition. About the larger fragments, the cement makes a crust of chlorite, quartz, carbonate, and colorless micaceous material, all growing normal to the fragments' surfaces. Fragments of foreign rocks appear to be present in the tuffs, along with carbonate veins.

### CONCLUSIONS

I. The conglomerate crops out in a rosary-like chain of northeasterly elongated hillocks, extended in the same direction at various topographic levels. They are made up of a roughly stratified, coarsely clastic, polymictic material cut by "veins" and "branches" of sandstone, with pebbles and boulders of various sizes, forms, composition, and degree of rounding, mostly of rocks not observed in the Nikitina Ravine area, and barren of organic and plant remains. All this suggests a fluvio-glacial origin as the components of a broken-up esker trending parallel to the glacial movement, i.e., from northeast to southwest.

As the glacier retreated, the esker was partially washed out, as evidenced by the zones of finely clastic material, wide in the southeast of the esker and separating the rosary-like conglomerate outcrops. These zones are made up of meta-shales with intercalations of coarser clastic material (sandstone and conglomerate). Subsequently, the esker was buried in shale. The glacier appears to have retreated fairly rapidly because some of the esker remained intact, in a characteristic ridge of gravel.

The south course of the Nikitina Ravine is made up of finely clastic material (meta-shale) with numerous beds of polymictic siltstone, silty sandstone, and sandstone, without any rhythm in the change of grain size and thickness. This suggests their deposition as ooze, under quiescent conditions, with a weak current, if any, at times growing strong enough to bring in silt and sand (siltstone and sandstone beds). The considerable amount of organic remains (graphite ?) in the meta-shale suggests an abundant flora.

Table 2

Spectrographic analyses of carbonate rocks (in %)

| Elements | Pebbles of the Nikitina Ravine conglomerate | | | | | Dolomitic limestones | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | 2 | | Bol'shoy Ptsitser Mts. | | Turovaya Bashnya | Blyb River | | Dzhentu Pass (Triassic) |
| | Specimen 147 | Specimen 455 | Specimen 475 | Specimen 204 | Specimen 290*/57 | Specimen 1858 | Specimen 1863 | Specimen 188*/57 | Specimen 1777 | Specimen 1778 | Specimen 1757 |
| Mn | 0.01—0.03 | 0.1—0.3 | 0.1—0.3 | 0.04—0.06 | 0.007—0.009 | 0.01—0.03 | 0.01—0.03 | 0.1—0.3 | 0.007—0.009 | 0.007—0.009 | 0.01—0.03 |
| Pb | — | 0.04—0.06 | 0.01—0.03 | — | — | — | — | — | — | — | — |
| Ga | — | 0.001—0.003 | — | — | — | — | — | — | — | — | — |
| V | — | 0.001—0.003 | — | — | — | — | — | — | — | — | 0.001—0.003 |
| Cu | — | 0.007—0.009 | 0.001—0.003 | — | — | 0.0004—0.0006 | 0.001—0.003 | 0.0004—0.0006 | — | — | — |
| Ag | — | 0.0001—0.0003 | — | — | — | — | — | — | — | — | — |
| Na | — | 1—3 | 0.1—0.6 | — | — | — | — | — | — | — | — |
| Ti | 0.4—0.06 | 0.007—0.009 | 0.04—0.06 | 0.01—0.03 | 0.04—0.06 | 0.01—0.03 | 0.01—0.03 | 0.007—0.009 | 0.004—0.006 | 0.004—0.006 | 0.1—0.3 |
| Ni | — | — | — | — | — | — | — | — | — | — | 0.01—0.03 |
| Zr | — | 0.004—0.006 | — | — | — | — | — | — | — | — | 0.007—0.009 |
| Mg | 0.7—0.9 | 0.4—0.6 | 0.4—0.6 | 0.1—0.3 | ~1 | 0.7—0.9 | 0.7—9 | ~1 | ~1 | ~1 | ~1 |
| Si | 0.4—0.6 | 4—6 | 7—9 | 0.1—0.3 | 1—3 | 0.7—0.9 | 0.1—0.3 | 0.1—0.3 | 0.04—0.06 | 0.04—0.06 | 0.4—0.6 |
| Al | 4—6 | 4—6 | 0.7—0.9 | 0.7—0.9 | 0.3 | 0.4—0.6 | 0.1—0.3 | 0.1—0.3 | 0.4—0.6 | 0.1—0.3 | 0.4—0.6 |
| Fe | 0.1—0.3 | 3—4 | 1% | 0.007—0.009 | 0.1—0.3 | ~1 | 0.07—0.09 | 0.007—0.009 | 0.001—0.003 | 0.001—0.003 | 1—3 |
| Cr | — | — | 0.001—0.003 | — | — | — | — | — | — | — | 0.001—0.003 |
| Sr | 0.01—0.03 | 0.04—0.06 | 0.04—0.06 | 0.01—0.03 | 0.04—0.06 | 0.04—0.06 | 0.04—0.06 | 0.01—0.03 | 0.04—0.06 | 0.04—0.06 | 0.01—0.03 |
| Ba | — | 0.04—0.6 | 0.01—0.03 | — | — | — | 0.004—0.00 | — | — | — | — |

* G.D. Afanass'yev's collection.
** V.V. Plashko's collection.

It appears that this part of the Nikitina Ravine was a segment of the outwash plain where glacial waters deposited their fine-grained load (meta-shale); a more intensive melting and a more rapid flow resulted in the deposition of coarser material (silt and sand). Numerous outcrops of Middle Devonian conglomerates have been discovered by A. A. Kadenskiy [4] and Yu. N. Khil'tov [12], in the Bol'shoy Zelenchuk valley; and by V. N. Robinson [7, 8] in the Marukh River valley, the Marukh — Bol'shoy Zelenchum watershed, and in the basin of Teberda and Malka Rivers. There are no published data on the origin of the conglomerates, except for the A. A. Kadenskiy statement [4] that "The presence of poorly sorted conglomerates suggests the proximity of dry land, in Middle Devonian time, probably a chain of islands whose erosion supplied material for these coarse clastics. Subject to erosion was the very Peredovoy Range (Ekhress Island), which brought about an accumulation of conglomerate containing pebbles of the underlying plagioclase and volcanic rocks."

It is quite probable that not all of the Malaya Laba — Malka conglomerates are of the same origin; present among them appear to be glacial formations whose identification will be possible only after a detailed study.

Evidence of ancient glaciation has been observed in many places of the world: according to B. F. Howell [13] in the sub-Precambrian of Central and Western China, South Australia, India, South and Central Africa, North America, south Norway, and in the pre-Lower Cambrian of Spitzbergen and Greenland; and according to A. Hadding [11], in Scandinavia. According to Howell [13], a late Proterozoic glaciation occurred in California; and an Ordovician glaciation in Argentina. N. M. Strakhov [10] notes a Carboniferous glaciation in South America, in the south of Africa, in India, and Australia; and a Permian glaciation in Australia. In the U. S. S. R., Proterozoic marine tillites have been studied by A. N. Churakov [14-17], over a considerable area in Siberia: in the Kuznetsk Alatau, east and west Sayan, Mountain Altai, and Yenisey Range. N. M. Strakhov [10] has this to say of the ancient glaciations; "Precambrian glacial deposits are concentrated in geosynclinal regions and are related to the more or less considerable islands existing there, at that time. This situation, in itself, predetermined the nature of the glacial phenomena, as more or less considerable mountain glaciers descending to lowlands."

The presence of a Middle Devonian (?) glaciation whose relicts we have recognized on the north slope of the Front Range, in the northwestern Caucasus, as well as the numerous exposures of conglomerate in the Malaya Laba — Malka area, may indicate the presence here of mountain glaciers descending from Middle Devonian (?) island highlands; the presence of quartz albitophyre tuff beds in the Nikitina Ravine fluvioglacial deposits suggests continuous Devonian (?) volcanic activity.

II. It is impossible to give the exact age of the Nikitina Ravine section, as yet, because the age of its constituent rocks, eroded and redeposited, is also unknown. Some students of the Caucasus [1, 3, 8] believe the Malaya Laba — Urup area rocks to be lower Paleozoic, while some others assign them to the middle Paleozoic [2, 9]. The Nikitina Ravine and Mt. Khatsavitaya section is regarded as Lower Devonian by G. D. Afanas'yev [1] and V. N. Robinson [7]; as undifferentiated Paleozoic ($Pz_{1+2}$), by A. Sh. Kubanov [5]; and as Middle Devonian (?), by A. A. Kadenskiy [4]. Thus, this section, as well as the underlying rocks, has been assigned by many students to the same era, either to the lower ($Cm$-$S_1$) or middle ($D_1$ or $D_2$?) Paleozoic.

The upper age boundary of the Nikitina Ravine section is marked by Lower (?) Carboniferous deposits, unconformable over them. It can be stated with certainty that the Nikitina Ravine deposits are younger than those of the Bol'shaya and Malaya Labas and Urup area; probably younger than the sulfide mineralization; and older than the Lower Carboniferous. Their exact age will be known when the age of the older Bol'shaya Laba — Urup area deposit has been determined. It is most likely Middle Devonian in age.

III. The finding of strongly pumpellyitized rocks underlying the Nikitina Ravine deposits, the first such rocks found in the North Caucasus, is of interest. These rocks, often altered to almost monomineral varieties, were originally intermediate to acid extrusives with interbedded sedimentary formations.

In the North and Middle Urals, pumpellyitization is known only for Silurian rocks; and only for the Voykar formation ($D_1$ - $D_2^1$) in the Polar Urals, according to V. V. Markin and N. P. Lupanova.

According to D. S. Korzhinskiy [6], pumpellyite is formed at a lower temperature stage of metamorphism, at shallow depths, usually as a contact alteration in granite intrusions in fractures. Further studies of the Caucasian greenstone section undoubtedly will reveal pumpellyitized rocks in other areas of the Peredovoy Range, as well (we have observed pumpellyitized rocks in the upper $D_{1-2}^2$? formation of the Urup area, as well as in the Bol'shaya Laba — Beskes watershed). Pumpellyitization is typical probably for some definite horizon, only, as is true for the Urals, so that such a horizon may be locally a marker for divisions of the Paleozoic.

Only a detailed and comprehensive study of the entire greenstone section of the Peredovoy Range in the northwestern Caucasus will give a clear idea of its origin, metamorphism, and age.

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# ON THE INTRUSIVE NATURE OF THE TUAPSE GRANODIORITE PORPHYRY[1]

by

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Recent studies in the western Caucasus have shed new light on the sequence of sedimentary and igneous formations in the west end of the Main Caucasian Range, their age, and origin.

This is also true to a considerable extent for igneous formations widely developed here, and believed for a long time to be sheets of quartz porphyry contemporaneous in age with the Jurassic sedimentary rocks enclosing them.

The geologic situation in the Tuapse region, in its broadest features, is as follows. The principal rocks are thick Toarcian-Aalenian shales with subordinate sandstone and siderite beds. Locally this alternation is flysch-like. The main structure of the region, the Goytkh anticlinorium, is made up of Lower Jurassic shale. Its axis trends southeast-northwest, somewhat northeast of the orographic Tuapsinka-Pshish drainage divide, sharply expressed in the relief.

This drainage divide is formed by the Tuapse granodiorite porphyry which make up the axial zone of the Main Caucasian Range at its northwestern end. The summits Lysaya, Dva Brata, Semashkho, and partly Indyuk, are the highest elevations in this zone which has the general southeast-northwest Caucasian trend. The Pshish-Pshekha watershed to the north, too, is made up of granodiorite porphyry, to a considerable extent. The total area of these outcrops within the Tuapse region is over 140 km$^2$ (Figure 1). O. S. Vyalov, who studied this area in 1931-1934 [26, 27], called these rocks quartz porphyry and believed them to be contemporaneous with the enclosing Toarcian-Aalenian shale. The same views are held by V. V. Belousov and B. M. Troshikhin [9, 10], who worked here in 1937-1939. L. A. Vardanyants, in his 1956 work [14], believes them to be "typical liparite tuff".

Granodiorite porphyry of this area forms large stock-like bodies (Figure 2), bedding sills, and local, gently dipping dikes unconformable with the enclosing shale. The clear fact of their cutting the Toarcian-Aalenian flysch-like section indicates that they are younger than the latter. This is also corroborated by the presence in them of post-Lower Jurassic diabase porphyry, as well as by the absolute-age determinations of the granodiorite porphyry by the K-Ar method. The figures obtained were on the order of 120 million years, which corresponds to the Middle Cretaceous of the Holmes scale.

Present in the southeastern part of the region (upper course of the right tributary of the Malyy Pshish and along the right tributary of the Pshish) are exposures of a thick, highly deformed volcanic-sedimentary section of alternating shale and tuffaceous breccia. The entire section is obviously unconformable with the underlying Toarcian-Aalenian deposits. It has been named the Altubinal, in a number of joint publications by G. D. Afanas'yev and this author. Its geology and composition were described long ago [6-8, 14]. Present among the assorted fragments in it, and often appearing to be volcanic bombs and lapilli, are fragments of dacite. These bombs are rounded to pear-like, with one end often extended; some of these bombs reach a large size (up to 0.5 x 1 m). They are similar in a number of features to granodiorite porphyry from the Semashkho, Dva Brata, Lysaya, and Shessi mountains. The intrusive and extrusive granodiorite porphyries are not much different in age from the Altubinal volcanic-sedimentary section, to which they are genetically related.

Without pausing for a description of these rocks, which has already been given [7, 13], we shall note only a few points. The granodiorite porphyries are massive, dense rocks, free of visible porosity (bubbles) which could be regarded as evidence of an incipient pumice-making process. Small amygdules filled with zeolites are rare exceptions. The microscope reveals a microfelsitic to felsitic, locally microgranite groundmass with immersed porphyroblasts of idiomorphic quartz, albite No. 5-8, and biotite scales. Present in small

[1]Ob intruzivnoy prirode granodiorit-porfirov tuapsinskogo rayone.

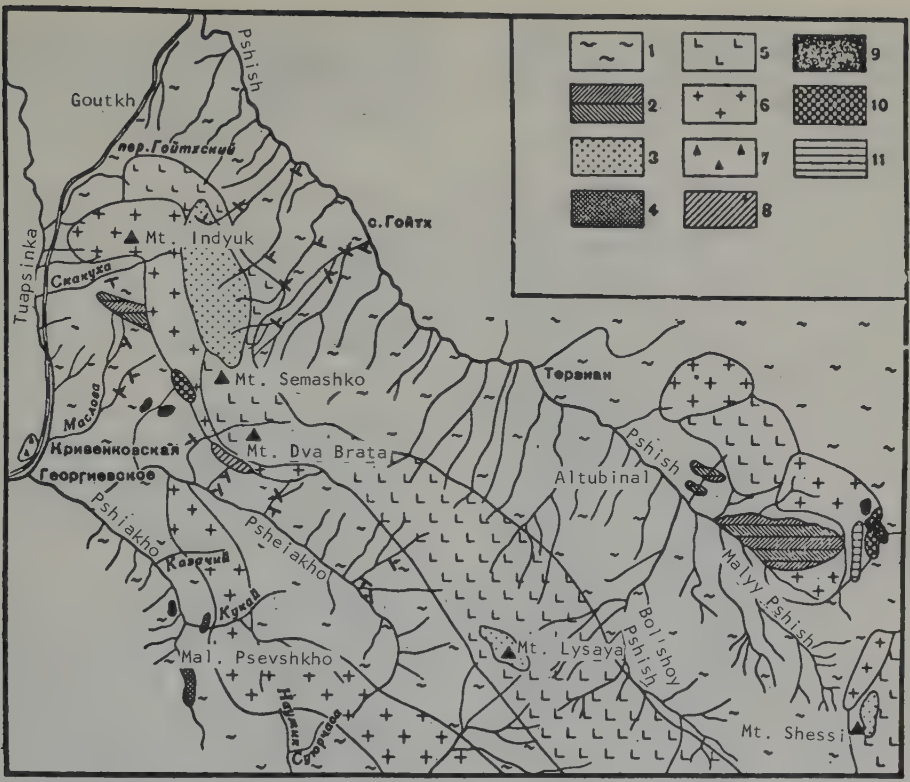


FIGURE 1. Geologic and petrographic map of the Pshish-Tuapsinka watershed in the Main Caucasian Range drainage-divide zone.

1 - Jurassic shale; 2 - Altubinal volcanic-sedimentary sequence; 3 - sandstone; 4 - diabase porphyrite; 5 - granodiorite porphyry; 6 - "extrusions" of the Mt. Indyuk-type; 7 - sodium-rich porphyry extrusions; 8 - eruptive breccia of the Mt. Dva Brata type; 9 - pyroxene gabbroid; 10 - eruptive breccia of the Mt. Semashkho type; 11 - drainage-divide eruptive breccia.

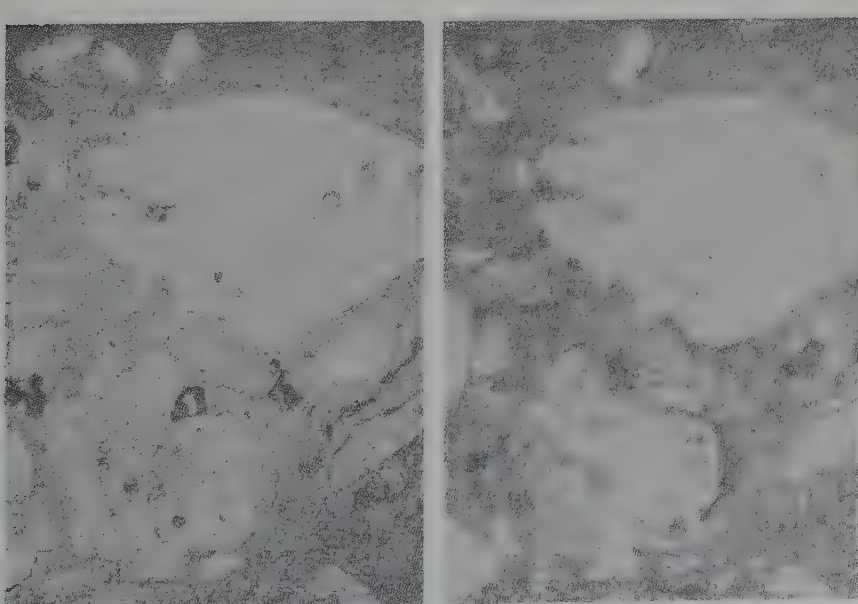

FIGURE 2. a) granodiorite porphyry, magnification 30 X, Nicols parallel; b) same, Nicols crossed.

amounts are sphene and garnet, with accessory zircon and apatite. Given below are the results of chemical analyses for granodiorite porphyry as well as its average mineral composition (Tables 1 and 2).

Table 1

Chemical analyses of the Tuapse granodiorite porphyry (A. Popova, Analyst)

| Oxides | Specimen 469/55 | Specimen 175/57 | Specimen 440/56 | Specimen 507/56 |
|---|---|---|---|---|
| $SiO_2$ | 66.60 | 66.08 | 68.38 | 66.97 |
| $TiO_2$ | 0.55 | — | — | — |
| $Al_2O_3$ | 14.63 | — | — | — |
| $Fe_2O_3$ | 2.53 | — | — | — |
| FeO | 2.14 | — | — | — |
| MnO | 0.09 | — | — | — |
| MgO | 1.79 | — | — | — |
| CaO | 1.35 | — | — | — |
| $Na_2O$ | 3.76 | 3.46 | 4.02 | 3.94 |
| $K_2O$ | 3.91 | 4.20 | 3.34 | 3.03 |
| $H_2O^-$ | 0.64 | — | — | — |
| $H_2O^+$ | 1.78 | — | — | — |
| Total | 99.82% | — | — | — |

The general lack of vesiculation in the granodiorite porphyry suggests that the magma was cooling-off under thermodynamic conditions precluding the formation of pumice. M. P. Volarovich and V. P. Chepurin [25], who experimented with heating water-bearing obsidian, under pressure, in order to determine the thermodynamic conditions of pumice-making, have found out that "the formation of pumice in acid lava flows can take place only at shallow depths. At a depth of 50 to 60 m corresponding to a pressure of 15 atm., pumice is not formed, even at the comparatively high temperature of 1200° C. This process can take place only at shallower depths. The temperature of the pumice-making process rises somewhat with depth. Although pumice is formed at the surface at 870 to 870° C, this process requires a temperature of 950 or 960° C at 16 to 20 m, where the pressure is about 5 atm; at 40 to 50 m, the initial pumice-making temperature rises to 1000° C."

Table 2

Qualitative mineral composition of the Tuapse Granodiorite porphyry (Average of 28 determinations)

| Minerals | by volume per cent |
|---|---|
| Groundmass | 65.6 |
| Quartz | 10.6 |
| Plagioclase | 23.8 |
| Biotite | Low |
| Total | 100 |

Thus, the absence of any evidence of incipient pumice-making process suggests either that 1) the granodiorite-porphyry massifs have been stabilized at depths exceeding those permitting the beginning of this process or 2) the loss of gas components by the magma, other than the 1.78% water determined by the analysis of stabilized granodiorite porphyry, took place gradually, somewhere on upper structural levels, during the rise of magma to the near-surface zone.

Experiments of N. I. Khitarov have established that silicate melts of a granite composition lose most of their gaseous component in these upper structural levels [46]. A gradual liberation of gases, possible only in relatively deeper reaches rather than very near the surface, is corroborated by other considerations, as well. Thus L. Greyton [30] believes that a maximum of 2 to 3% of solution gases is the limit at which a quiet extrusion is possible. He states, "If, for instance, the volatile content be assumed to be 5 to 11% (according to N. I. Khitarov's experimental data [46], it is 6% for granite magmas, at T = 1000° and a pressure of 3000 kgm/cm$^2$ — A. B.), as a limit of solubility for various common magmas, of 2 to 3% volatiles may turn out to be the maximum for a quiet extrusion, while the melt with a volatile content higher than this "critical" one will have an explosive eruption."

We deal here, then, with a catastrophic near-surface liberation of these 2 to 3% gases, while the magma itself arose from the depths too fast to lose any sizable portion of them. This portion of the gases constitutes an explosive charge which sets off the eruption.

Ye. K. Markhinin [40, 41] notes that only 0.55% water liberated from magma is sufficient to bring about a mighty explosion like that of the Bezymyannyy volcanic eruption. He believes that liberation of 1%, and even of a fraction (not less than 0.1%) of it, by volume, of magma water is sufficient to produce strong volcanic explosions.

We must assume, then, that if the original silicate melt of granodiorite porphyry had come up to the surface, the amount of its solution gases would have but slightly exceeded 1.78%, typical of the water content in a solidified lava (Figure 1). This important point should be kept in mind.

Experimental and field work of many investigators has established that the viscosity of a silicate melt depends to a considerable extent on its composition. Acid melts are the more viscous, and a rise in acidity brings about a proportionate rise in viscosity. In studying the viscosity of molten rocks with different $SiO_2$ contents, M. P. Volarovich and L. I. Korchemkin determined their qualitative relationship, using the F. Yu. Levinson-Lessing acidity factor [17, 18, 20, 22] as the quantity characterizing a given rock composition. They have derived a formula for this relationship, from the 1400°C isotherm:

$$\log \eta_{1400^\circ} = -\frac{23.9}{a + 1.1} + 10.5,$$

where $\eta$ is viscosity in poises, at 1400°C; quantities 23.9 and 1.1 are empirical constants; $\alpha$ is the Levinson-Lessing acidity factor; and 10.5 is the logarithm of viscosity for quartz glass, in poises, at 1400°C.

As seen from this formula, log $\eta$ approaches, for a higher $\alpha$, a certain limit, equal to 10.5, which is the viscosity logarithm for quartz glass at 1400°C where the acidity factor is assumed to be infinity.

The acidity factor for the Tuapse granodiorite porphyry, calculated from a chemical analysis of specimen 469/56, is $\alpha = 3.3$. Applying the formula, we find that $\log \eta_{1400^\circ}$ for them is 5.1. This means that the granodiorite porphyry viscosity at 1400°C is on the order of $10^5$ poises.

A number of works by M. P. Volarovich, L. I. Korchemkin, A. A. Leont'yev, D. M. Tolstoy, and others [18, 20, 21, 23, 34], have established the temperature-viscosity relationship for silicate melts with a constant composition. Figure 3 presents the curves of such a relationship for the Alagez volcano.

In this diagram, temperature is plotted along the abscissa axis, and log $\eta$ along the ordinate axis. It appears that the Alagez alkalic dacite has a viscosity of about 4.5 poises, at 1400°C; and of $10^{6.5}$ poises, at 1100°. According to the chemical analysis cited in the reference [22], the acidity factor for this rock is $\alpha = 3.26$.

An analysis of these and other temperature-viscosity curves (Figure 4) [20, 22, 23] leads to the conclusion that a 100°C temperature drop in silica-rich rocks raises their viscosity by about one order. In the event of our granodiorite-porphyry melt reaching the surface, its temperature could not have been higher than 900 to 1000°. This is in accord with modern concepts of theoretical volcanology, based on observations of active volcanoes, and with the corresponding calculations. Indeed, a magma rising from depths to the surface must undergo considerable cooling because of the gas escape, the loss of latent heat of melting, and a change of thermal energy to mechanical, in the process of moving into upper structural levels; also because of heat radiation near the surface and of the loss of heat to the enclosing colder rocks.

Assuming that 1000°C is the temperature limit for a surfaced acid lava, we may arrive, by extrapolation, at the viscosity of a surfaced silicate melt with the composition of our granodiorite porphyry. Obviously, the viscosity of such a lava will be on the order of $10^8$ poises.

Besides, a surfaced lava should contain an average of over 35% of the solid crystalline phase represented by phenocrysts (Figure 2); and the presence of such a solid phase in a melt appreciably raises its viscosity.

It has been experimentally established [21, 38] that in all of the crystalline rocks tested, viscosity in the softening range is considerably higher than in any of the glasses manufactured from them, by a factor of 500 to 1000, depending on the structure of the sample. The softening range viscosity is higher in those rocks with a larger number of phenocrysts and with a more fully crystallized groundmass. This viscosity rise in partially crystallized melts is apparently due to two causes: a mechanical effect of the solid phase; and a more acid, richer in $SiO_2$, composition of the groundmass, (as compared with the over-all composition of the rocks). In the softening range, on the other hand, which corresponds to a certain extent to the state of a surfaced magma, the viscosity of the melt is determined by the properties of the basic, uncrystallized magma.

Considering all that, we may assume $10^{10}$

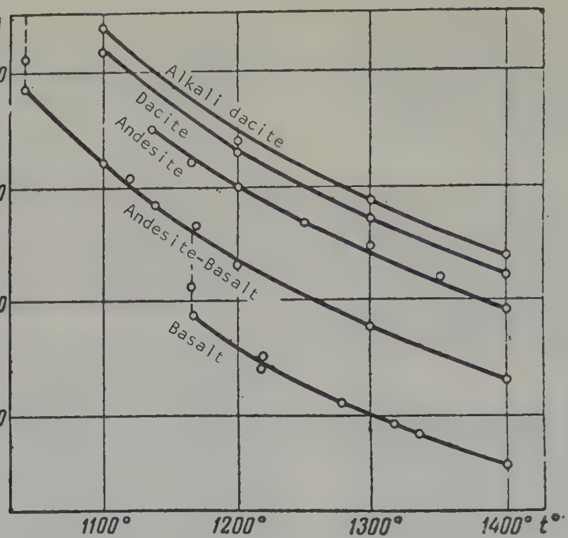


FIGURE 3. Temperature-viscosity curves for molten lavas from Alagez; after M.P. Volarovich [22].

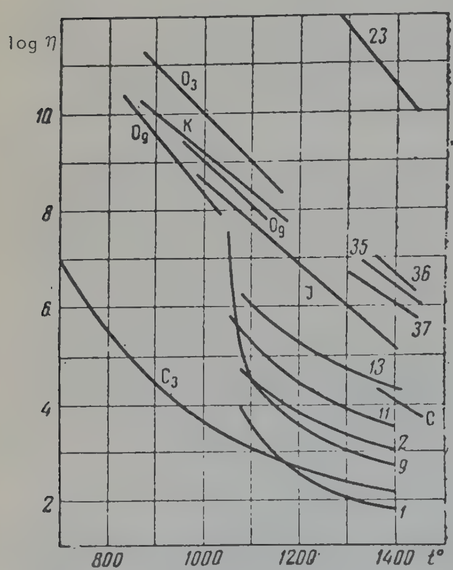


FIGURE 4. Temperature-viscosity curves for rocks (basic and acid); after M.P. Volarovich

1 - basalt from the Transcaucasus; 2 - teschenite from Kursebi; 9 - Vesuvius leucitic lava; 11 - andesite-basalt from Alagez; 13 - dacite from Alagez; $O_3$ - obsidian from Alagez; $O_9$ - Obsidian from Ani; K - kulibinite — Transbaykalian volcanic glass with 6.02% volatile water; 23 - quartz glass; $C_3$ - common industrial glass with about 70% $SiO_2$; 35 - hornblende granite from ? ; 36 - liparite from Niyim; 37 0 the Oka obsidian; 1 - tektite from Indo-China (indochinite, a vitreous meteorite); C - the Saratov 1928 stony meteorite, with 24% MgO.

poises as the lowest possible viscosity for a surfaced degassed liparite-dacite lava corresponding to our granodiorite in composition. However, this source magma of our granodiorite porphyry did contain dissolved gases.

What has been said in the beginning of this article leads to the assumption that the gas component of our surfaced silicate melt could hardly have differed much from the 1.78% typical water content in a stabilized rock. However, even this amount of dissolved gases is enough to lower the viscosity of a melt appreciably.

Is it possible to get an idea of the viscosity of a liparite-dacite silicate melt with a volatile content of 1.78%? A. A. Leont'yeva, in studying the temperature-viscosity relationship for obsidian and water-containing glasses [38], has established that kulibinite (volcanic glass from Mt. Krestovaya, in Transbaykalia), with 70.238% $SiO_2$, 11.508% $Al_2O_3$; losses in heating, 60.02% had a viscosity of $10^{9.2}$ poises, at 1000°C; and $10^{10}$ poises at 900°C. Obsidian No. 8 from Kamchatka, with a loss in heating of 1.0%, had a viscosity of about $10^9$ poises, at 870°C. It should be kept in mind that the glasses tested were homogeneous, free of a solid phenocryst phase which would raise their viscosity appreciably.

Thus we have every right to assume $10^8$ to $10^9$ poises as the viscosity of a silicate melt with a composition of the Tuapse grandiorite porphyry, and a volatile content of about 1.78% under surface conditions. It is quite interesting to compare these figures with those for road tars. N. N. Korotkevich states [35] that

viscosity of bitumen No. 1, high among such materials, is about $10^4$ poises, at 40°C (Figure 5). In other words, the viscosity of our melt, under surface conditions, is 100,000 times higher than that for bitumen No. 1, used in road beds, at 40°C. It is improbable that lavas of such viscosity would spread in sheets over considerable areas.

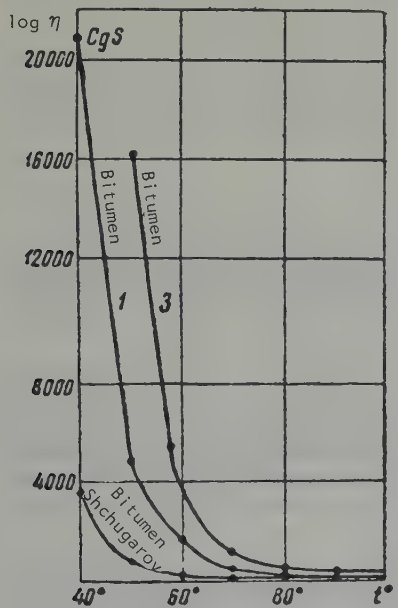


FIGURE 5. Temperature-viscosity curves for bitumens; after N.N. Korotkevich.

Silicate melts of such a high viscosity can either solidify on their way to the surface or be squeezed out as obelisk-like and domal extrusive bodies. (Mont-Pelée, Katarman in the Mindanao Sea, the Merapi domes, etc.)

Our arguments are fully corroborated by volcanologic data from various parts of the world. For instance, R. Van Bemmelen [12] notes, on the basis of his study of Indonesian volcanism, a growth in explosive power with increase in acidity of magmas, as a general tendency in all Pacific volcanoes. He states, "Viscosity of an outpouring magma rises with its silica content. The more acid andesites and decites, when they are low in volatiles, have a tendency to form domes, in places with short and thick tongues protruding from their base."

Many such domes are present in Indonesia (volcanoes Halunggung, Kelud, Katarman in the Mindanao Sea; Merapi, etc.). Most of the extensive liparite and liparite-dacite flows described in the world literature (P. Marshall, K. Fenner, J. Westerveld, R. Van Bemmelen, A.N. Zavaritskiy, V.P. Petrov, M.A. Favorskaya, etc.) appear to have been the deposits of incandescent sandy flows of crystal fragments and pulverized volcanic glass in an atmosphere of a hot juvenile volcanic glass. Such flows are quite mobile and capable of spreading over large areas. Upon being deposited, they form clinkers and ignimbrites, in general barely or not at all distinguishable from normal lavas. Among such deposits are the Katman rhyolite tuffs in the Valley of the Ten Thousand Smokes [47]; the clinkered rhyolite tuffs in the North Island of New Zealand [50]; "liparites" of the Pasum area in south Sumatra; and finally the immense bodies of the Toba tuffs in north Sumatra, described as "quartz trachyte", "quartz trachyandesite", "liparite", and "rhyolite", prior to J. Westerveld's works [52]. In the Soviet Union, considerable outcrops of ignimbrite are known from Armenia [1, 9, 11, 31, 33, 36, 37, 43], the Chegem-Baksan region in the northern Caucasus [42], and in the Far East [44].

The Tuapse granodiorite porphyry occupying an area of over 140 km$^2$, does not have any of the occurrence and structural features of ignimbrites. For the reasons cited above, they cannot be regarded as lava flows contemporaneous with the enclosing Jurassic shale. A study of the geologic position of this granodiorite, its physical composition and structure, as well as absolute age, indicates that it is younger than the enclosing rocks (120 million years). What has been said above, too, suggests that "this granodiorite porphyry is an intrusive hypabyssal formation, changing in places to an extrusive facies in necks and domes filling up volcanic vents."

The relationships between the Altubinal and volcanic-sedimentary section, mentioned in the beginning of this article, and the granodiorite porphyry, appear to be as follows. The Altubinal breccia is represented by tuffaceous material ejected from central type volcanoes, with fragments of rocks forming the walls of volcanic channels and with bombs and lapilli formed partly in the destruction of a very viscous silicate plug. Such a plug was moving in front of the rising magma and from time to time blocked the volcanic vent.

Upon reaching a certain level, this plug turned to froth and exploded because of a sudden liberation of gases. The origin of the Altubinal volcanic-sedimentary section of sedimentary and pyroclastic material occurred during such a period of volcanic activity.

Periods of intensive volcanic activity changed to periods of quiescence and of normal deposition of sedimentary material. At later stages, the formation of pyroclastic material ceased because the volcanic vent was completely blocked by the growing dome or obelisk of a very viscous cooling magma. The energy of the

magmatic hearths was inadequate to break up the plug so formed. The silicate melt, having risen to near-surface levels but without an outlet, solidified as sills and stock-like bodies, and in places in small and gently dipping granodiorite porphyry dikes.

The structural difference in granodiorite porphyries, expressed in the various degrees of crystallization of the groundmass and in the quantitative relationships with the phenocrysts as well as in the size of the phenocrysts, is determined to a considerable extent by the rate of cooling of the magma; this rate, in turn, depends on the size of the magmatic body and on its proximity to the surface. This is why the granodiorite porphyry of large intrusive massifs is micrograniti̇c, while it is felsitic to microfelsitic in the contact zones. The minor dike-like granodiorite porphyry bodies, present in many places in the immediate vicinity of the main massif, are very slightly crystallized; the volume of their groundmass is much larger than that of the phenocrysts, and the groundmass is microfelsitic and locally cryptolitic.

The conditions of formation of the Tuapse area granodiorite porphyries are a combination of intrusive and extrusive processes. This combination is typical of post-Jurassic igneous phenomena in the west end of the Main Caucasian Range. Specific features of geologic position and petrology of a number of igneous formations in the West Caucasus can be interpreted in the light of such a combination.

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# METHODS

## METHOD OF UNDERWATER GEOLOGIC AND GEOMORPHOLOGIC STUDIES[1]

by

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Underwater sport and scientific study have been becoming more and more popular. Aqualungs are being widely used, everywhere. Lovers of sport and underwater hunting, archeologists looking for submarine ruins of ancient cities and sunken ships, and marine biologists now are able to see for themselves the submarine world and to get acquainted with sea denizens, "at home".

But little has been written on underwater geologic and geomorphologic studies, although students of the littoral zone may find just as many interesting things at the sea bottom as the biologist and archeologist. The value of direct observations of the geology and structure of a littoral slope need not be repeated here, although it did not attract much attention until the last decade. The important thing to do was to study and describe the elements of surface relief and structure, although they are now known to be but incomplete expressions of the evolution of the sea [6, 7, 11]. It has been established that a development of surface relief occurs only after certain definite changes in the submarine littoral slope. It is here that the basic littoral processes take place: a transformation of the energy of incoming waves and displacement of immense volumes of clastic material. The peculiar irreversible littoral relief is also formed here by the action of waves and wave currents. All this demonstrates the importance of underwater study of the geomorphology of coasts, and the necessity for methods of such study, with the fairly advanced equipment now on hand.[2]

Light diving equipment was first used for geologic work along the U. S. S. R. coasts as early as before the war. The necessity for direct bottom observations became evident because of the exceptional diversity of bottom facies. In the words of V. P. Zenkovich [5-a], "Neither the detailed depth measurements nor the use of bottom core barrels, sand samplers, etc., will reveal the details of this environment. The method of direct observation is the only acceptable one, under such conditions." He was the first to study some interesting forms of bottom relief. For instance, at the bottom of a bay, at a depth of over 2 m, he discovered a well preserved ancient abrasion escarpment, up to 3 m high. In the following year, he studied, in a light-weight diving suit, the movement of pebbly sands at the bottom, during a swell [8].

By now, underwater studies have become routine in the dynamics and morphology of the coasts. They were especially widely used by V. P. Zenkevich, V. I. Budanov, and A. S. Ionin, in the Black Sea [9]; by A. S. Ionin in the Sea of Japan; and by O. K. Leont'yev in the Caspian Sea [12]. O. K. Leont'yev and his assistants, diving with light-weight oxygen equipment, made a structural geological survey of the Caspian bottom along the Daghestan coast, measuring with an underwater mining compass strikes and dips of limestone. A mapping of bottom ridges made it possible to outline oil-bearing submerged anticlines along the Daghestan Caspian coast.

Underwater geology has become popular abroad, as well [14]. For example, in 1953 a group of American geologists surveyed a bottom area of about 1000 square miles off southern California [15], at depths down to 30 m, with aqualung equipment. A detailed 1:54,000 geologic map was compiled as a result of that work. It is of interest that this map is based on a triangulation grid laid out in the sea, with buoys for triangulation markers.

In 1949, V. I. Budanov [3] used underwater photography in geologic and geomorphologic studies of a coastal zone for the first time. He

[1]Metodika podvodnykh geologo-geomorfologicheskikh issledovaniy.

[2]Here we barely touch upon diving equipment and its use. This subject has been fully covered elsewhere [2, 13].

used a "robot" camera with automatic shutter for 25 frames. V. I. Budanov and A. S. Ionov, working with ISAM-48 diving equipment, succeeded in obtaining satisfactory photographs of bottom deposits and relief forms, down to depths of 4 to 7 m with this camera.

However, the use of oxygen diving equipment restricted the scope of underwater study, because ISAM-48 and IPSA diving suits are not operative below 20 m; in addition, they are fairly complex and restrict free swimming over the bottom.

Very promising for underwater work is the air-carrying skin-diving equipment, manufactured in this country: Aqualungs ABM-1 (Podvodnik-1). They are extremely simple to operate, and are effective to depths of 60 m, i. e., adequate to explore practically all of the submarine slope within the wave-action zone. In addition, diving goggles give a wide field of vision, while fins provide for fast locomotion. The underwater compass and depth gauge are good means of orientation.

With such equipment, underwater geologic and geomorphologic studies yield data almost as good as that gathered on land.

In the Oceanology Institute of the Academy of Sciences, U. S. S. R., aqualungs have been used since 1957. In 1958, one of the authors carried out underwater exploration in Poland, where he collected interesting material on the bottom structure and sand drifts of the Baltic littoral zone [10]. The first underwater geomorphologic expedition was organized by the same institution in the Black Sea, in 1959. Its purpose was a study of the littoral slope structure along the East Crimea and Caucasus, the abrasion rate of the coast, etc. Much attention was paid to methods of under water study. Participating in this work, besides the authors, were V. P. Zenkevich and diving instructor Ye. S. Vasil'yev. For underwater work, the expedition had at its disposal six ABM-1 aqualungs and a PZUS compressor.

Underwater work of studying the littoral zone consists of the following operations:

1) Measuring the depth and collecting samples of bottom sediments and bedrock;

2) study of the bottom, geologic mapping, and photographing significant relief forms;

3) setting up control areas and markers to observe the coast abrasion rate;

4) submarine leveling;

5) photographing the bottom along a given line;

6) taking moving pictures, especially of sand particles in bottom drifts.

An important field of work in the dynamics and morphology of seashores is depth measurement with sampling of the bottom at various depths, in order to determine the profile and structure of a littoral slope [3, 4]. However, such sampling, done from a ship, at isolated points of the bottom, does not give an accurate picture of bottom deposits. In addition, in sampling from a ship, when the bottom is invisible, there is always the chance of obtaining accidental, non-typical, samples. This is especially true for a littoral zone where the facies composition of bottom deposits is quite diversified. With the help of light-weight equipment, it is possible to determine the exact distribution of drifts over the bottom, as well as the regularity of structural changes with depth; in addition to the sediments, bedrock can be sampled and its occurrence elements determined.

Underwater study of a littoral slope and its sediments proceeds as follows. Having taken a bearing with the underwater compass, the diver descends the slope, away from the shore, and proceeds underwater, maintaining the same bearing. All changes in the bottom sediments are photographed. Whenever necessary, samples are taken at typical points whose depth is determined with the depth gauge; in that way the sample-depth association is established. Working on a steep slope, a single diver rapidly reaches a boundary of the wave-action zone.

Along the east Crimean coast of the Black Sea we have observed abrupt changes in the structure of the littoral slope, down approximately to 15 or 20 m, after which the bottom was quite monotonous. Along the north Caucasian coast, on the other hand, submarine ridges, although poorly expressed in relief, were traceable to depths of about 40 m. When the bottom is flat and the changes in depth slow, the divers can take turns or go part of the way in a boat. Generally speaking, when precise data on the bottom changes are required, diving work should be combined with that from a boat or ship. In this operation, the distance from the water edge is determined with a theodolite, from a rod installed on the boat, when the diver signals a change in the bottom sediments. Of course, such operations call for good communication between the diver and the boat.

In some places, a general idea of the bottom structure and sediments can be obtained with no more equipment than fins, goggles, and a depth gauge. One of the authors of this article, in running a reconnaissance traverse, had to investigate a coastal slope with littoral swells without any diving equipment. Every 4 or 5 km of the traverse, he swam out, normal to the shoreline, determined with the depth gauge the elevation of the submarine swells above the bottom, and identified the nature of drifts on and between the swells. In that way, it was

possible to trace general structural changes in the submarine slope and the association of bottom sediment and relief forms. These observations were supplemented later by the study of aerial photographs (taken during the surveying). Specifically, distances from the water edge to the crests of swells and the troughs between them were taken from the aerial photographs. Data obtained during the diving were used in drawing the profiles of the coastal slope in the swell zone. To be sure, the use of aqualungs would have made this study more complete.

Of great importance in the work in littoral zones is the underwater study of abrasion and accumulation relief forms. In such investigations, one must describe and, if possible, photograph and plot on a map submarine ridges, niches, grottos, escarpments, sediment accumulations, and all other relief forms of the littoral slope, along with fauna and distribution of algae. The dimensions of such forms are measured, as well as their depth, trend, and elements of occurrence of their rocks. When necessary, samples should be taken of unconsolidated sediments as well as of bedrock (with a hammer, for the latter). In a word, modern equipment (aqualungs, cameras, submarine compasses, depth gauges) provide the geomorphologist with means of studying submarine relief of the coastal zone, in as much detail and practically in the same way as it is done on land. The diver even has an advantage over the student of land relief: by moving freely up and down in the water, he can readily investigate sheer cliffs and exposures, accessible with difficulty on land.

In our 1959 work in the Black Sea, we used a "Zorkiy 4-S" underwater camera in a waterproof Plexiglass box with outside levers controlling the winding of film, focusing, and speed; also the domestic PF-3 fluororthochromic film, highly sensitive in the green range of spectrum. The film choice appears to be a sound one: all other factors being favorable, it gives quite satisfactory negatives.

We photographed the abrasion forms (mushroom-like blocks, grottos, ridges, etc.) from more than one position. In this respect, underwater photography has certain advantages: it is possible to take pictures from most improbable angles, impossible on land, thus selecting the best view. It is also possible to draw underwater sketches of interesting relief forms and to jot down a few notes with a common lead pencil on plastic or plywood tablets. The photographs, the sketches, and the notes constitute very valuable material in studying the structure of a littoral slope. Fairly detailed geologic and geomorphologic maps of bottom areas can be compiled in the course of such work.

In our study of the abrasion rate of Black Sea shores, we set up benchmarks in several places along the coast, near Karadag and Gelendzhik; tied in to these markers was a survey of some adjacent coastal areas. These benchmarks, to be resurveyed in later years, were cemented in holes drilled in the bottom and in the cliffs. They are steel rods, diameter 15 to 20 mm, standing 5 to 10 cm above the bottom or cliff. To evaluate the relief changes in various zones of the littoral slope, several benchmarks were set up in each area, aligned normal to the water's edge. The direction line was traced with a theodolite set up over the basal shore marker. A cable, graduated into meters and with a weight attached to its seaward end, was stretched from the instrument station to a boat. With the cable stretched tight and the boat in the theodolite field of vision, i. e., on the line, the weight was dropped. On the bottom, and with the cable stretched, the benchmark points are readily selected. We tried to locate them at points of different relief, for example between swells, on top of a ridge, on an even slope, etc. The benchmark holes were drilled in rocks with a RPM-17a pneumatic drill with pobedite-tipped bits. Compressed air for the drill was fed through a high-pressure hose from a 40-liter transport balloon, with a 150 atm pressure maintained by a PZUS compressor. The operative pressure was lowered by means of a RS-250-48 reductor connected to the drill with a hose. Ordinarily, one balloon of air is enough to drill a 10 to 15 cm deep hole in tough surface rocks. Underwater drilling is slower because of the strong vibration of the drill, making it difficult to hold it in the same position. The underwater driller can gain some stability by putting on additional weight (no less than 5 to 6 kg). In addition, a small hole for the drill should be chipped out with a chisel. Two 40-liter balloons of air are required, as a rule, to drill a bottom hole in hard rocks, so that the operation takes no less than 4 or 5 hours, counting the time for filling up the balloons. Drilling on land can be done by two men, where three are needed in underwater drilling. One man, in the boat, controls the flow of air from the compressor to the drill, while two men do the drilling at the bottom. One of them holds and directs the drill at the very bottom, to overcome the effect of vibration; the other operates the drill. A reliable communication system must be established between the two ends of the operation.

The cementing of benchmarks is not as laborious. The diver descends to the bottom with a bag of cement slurry and squeezes it out in the hole. A hard cement film is rapidly formed. The cement at the base of the rod is covered with a rag and a layer of sediment.

The lines laid out in this way were used in instrument leveling of the littoral slope; the elevation of markers above the bottom as well

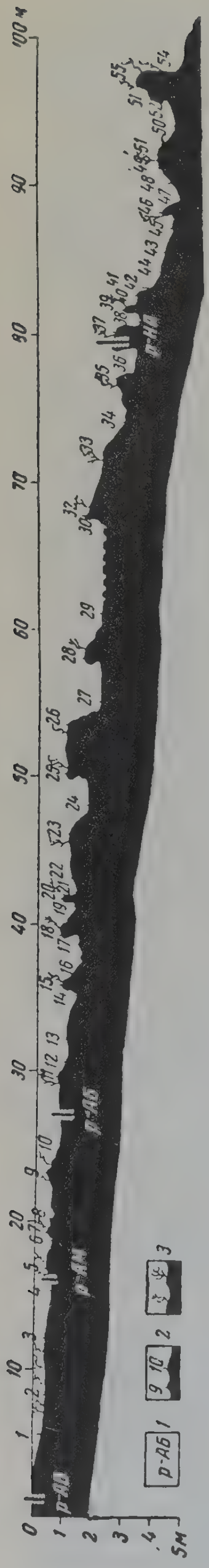

FIGURE 1. Leveling profile of a littoral slope with a ridge relief in an area along the Black Sea coast.

1 - benchmarks; 2 - intermediate points and rod stations; 3 - algal growth on bottom.

as their distance from the water's edge, were measured during this operation (Figure 1). The readings were taken with the leveling instrument, on a rod set up by the diver on benchmarks and at intermediate points. The standard 4-meter rod could be used only down to depths of 2 to 2.5 m. Therefore, beginning with a two-meter depth, we used a 5-meter metal extension arm, which enabled us to take readings down to 7 or 8 m. The divers had much difficulty in holding the rod straight, because even gentle waves tended to tilt it. To make the rods more stable, a fairly heavy weight was attached to the extension arm, also supported by the rodman. The rod position was controlled from the boat which followed the diver and signaled to him the end of each reading. Ordinarily it took four men and 1.5 to 2 hrs for the detailed leveling of 100 to 150 m. To be sure, such underwater leveling can be done without fixed benchmarks, and to greater depths, depending on the purpose. The method of work will probably be the same, the important thing being to determine the position and bearing of the leveling traverse. Naturally, a longer rod will be needed to continue a traverse farther out to sea.

The next step in underwater work was to photograph the bottom along the same lines or leveling traverses. As a routine procedure, we would take a series of overlapping vertical photographs. Placed within each area photographed was a measuring rod with decimeter graduations, for scale (Figure 2). This rod, besides being a measure for bottom objects, was a means for "reducing" all photographs to the same scale, because it was impossible to take all photographs from the same height above bottom. As a rule, two men participated in this operation: one placed the rod on the bottom, and the other took pictures. A series of overlapping photographs, like that of aerial land photographs, give an idea of changes in the bottom structure, at depths from 1.5 m to 10 m. A repeated leveling and photographing of the bottom determines with adequate certainty the nature of its changes for a certain period of time.

In addition to underground photography, underground cinematography has become quite popular, as witness the splendid submarine moving pictures demonstrated in the last few years on a wide screen. The study of littoral geomorphology is made more representative through reproduction of submarine landscapes and of interesting relief forms. Even more important for scientific study are moving pictures of bottom sediments. This work is fraught with many difficulties because the bottom drifts are set in motion only by waves which make it difficult for the cameraman to maintain his balance; at the same time, the rising turbidity renders the lighting that much poorer. For this reason, such pictures can be taken ordinarily at the beginning of a stormy stage, while the

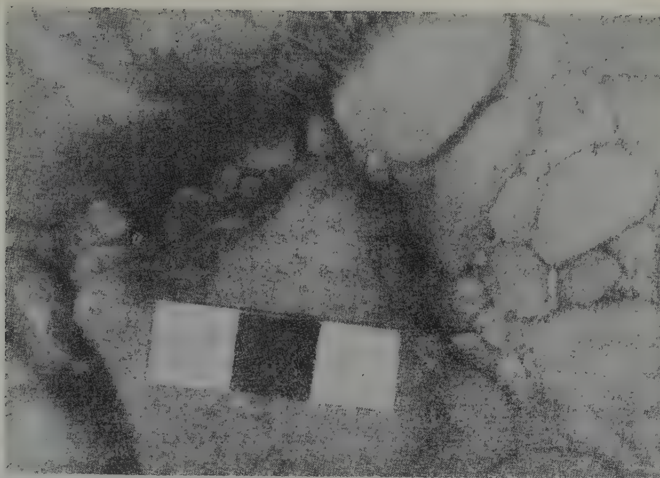

FIGURE 2. Vertial photograph of bottom, with a rod for scale.

amplitude of the movements of bottom sediments is slight.

Some experience has been gained in observing the movement of bottom sediments in an agitated sea, with light diving equipment. We have already mentioned the work in this field by V. P. Zenkovich. N. A. Aybulatov observed the movement of sandy material and of fluorescein-colored water, in a fairly agitated sea [1]. He and his party used ISAM-48 light-weight oxygen equipment, more convenient than aqualungs, in agitated waters, because of its lighter weight; the light weight is important in coming up, when waves knock the diver off his feet. In addition, it lets the diver stay longer underwater and it comes with tighter fitting goggles which stay on under strong wave action.

Light-weight diving equipment, especially aqualungs, has just started gaining in popularity for submarine geology. A further improvement in equipment and methods of submarine study will increase its application.

This is a report of initial submarine geomorphologic study on a large scale. Undoubtedly, the scope of this work will grow from year to year. The authors will regard their goal as fulfilled if this article will be of assistance in the planning of new underwater geologic and geomorphologic work.

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# CHRONICLE

## ANNUAL SCIENTIFIC SESSION OF THE ACADEMIC COUNCIL OF THE GEOLOGICAL INSTITUTE, ACADEMY OF SCIENCES U. S. S. R.[1]

by

M. S. Markov

The annual session of the Academic Council was held at the Geological Institute, on April 18-20, 1960. Ten papers were read before an audience of over 100 geologists from 15 institutions of scientific research and industrial organizations.

The following four papers were on stratigraphy.

1. B. M. Keller, K. A. Kazakov, S. V. Nuzhnov, I. N. Krylov, and M. A. Semikhatov reported on "New Data on Stratigraphic Subdivision of the Precambrian" (See Izvestiya Academy of Sciences, U. S. S. R., geol. ser., No. 12, 1960).

2. I. T. Zhuravleva, V. V. Khomentovskiy, and L. N. Repina, "Lower Cambrian in Gornyy Altai" (to be published in Izvestiya).

3. V. A. Vakhrameyev's paper, "Specific Features in the Evolution of Upper Jurassic and Lower Cretaceous Floras of Siberia and the Far East and Paleobotanical Substantiation for the Stratigraphy of Corresponding Continental Deposits", presented a correlation table of Upper Jurassic and Lower Cretaceous deposits from the Lena, Upper Aldan, Bureya, and in part of the Zyryansk coal regions within the Siberian paleofloral province. Index assemblages have been designated for the Upper Jurassic, Neocomian, Aptian, and Albian. It was demonstrated that the Lower Cretaceous plant assemblage in the South Maritime Province differs sharply from the contemporaneous assemblage for those regions, because it belongs to the Japan-Indo-European paleofloral province.

The comparative analysis of flows for individual regions of the Siberian paleofloral province even now suggests the presence in it of three separate provinces: the Amur, Lena, and Arctic.

In discussing this paper, V. V. Menner noted the great importance of studying Mesozoic faunas, for paleoclimatology as well as for stratigraphy. He recommended for the future to take into account the data on Mesozoic floras of Scandinavia and Canada, in order to draw more definite boundaries between paleofloral provinces.

4. V. G. Morozova reported on a zonal scale for Danian-Montian deposits and on the Cretaceous-Paleogene boundary.

The study of foraminifera from Danian-Montian deposits of the Boreal (Russian Platform) and Mediterranean (Crimea, Caucasus) provinces has made it possible to detail the stratigraphy of Cretaceous-Paleogene boundary horizons. The Maastrichtian deposits carry an assemblage of Globotruncana, Rugoglobigerina, Pseudotextularia, costate Gumbellina, Lituola, and Orbignyina, which disappear at the contact with the Danian.

A great change in the systematic composition took place at the Maastrichtian-Danian boundary, with the appearance of new Tertiary forms and a change in the ecologic aspect of foraminifera, which suggests major changes in paleogeography. The change in paleocenoses and in the ratio of planktonic to benthonic foraminifera suggests a cyclic alternation of transgressions and regressions, with each stage (Danian, Montian, Thanetian) characterized by a foraminiferal stage of its own. At the same time, the Danian-Montian deposits belong to a major Paleocene sedimentary cycle and should be assigned to the Tertiary. A. L. Yanshin and M. M. Moskvin noted that the correlation of these zones with the Danian type section is still not clear.

[1]O godichnoy nauchnoy sessii uchenogo soveta geologicheskogo instituta Akad. Nauk S.S.S.R.

The discussion of tectonics opened with Ye. V. Pavlovskiy's paper, "The Structure and Development of 'Hercinian massifs' of France and South Germany" (see Izvestiya, ser. geol., Nos. 9 and 11, 1960).

M. V. Muratov noted in his paper, "Main Stages in the History of Tectonic Development in the Alpine Folded Province of South Europe", that this folded province had developed on a Paleozoic folding (Hercinian). The Paleozoic folded basement crops out in median massifs and in the cores of large anticlinoria within the Alpine province, and also fringes it. In the early Mesozoic, the Paleozoic basement was truncated and covered throughout most of the Alpine folded province by a comparatively poorly differentiated mantle of carbonate rocks locally interbedded with extrusives and siliceous formations. Deep geosynclinal troughs (Inner-Dinaric, Pennine, and Crimean-Caucasian) were formed only in three provinces: in the interior of the Dinarids, in the Triassic; in the Alps and the Caucasus, from the beginning of the Jurassic on. The close of the Jurassic and the onset of the Cretaceous witnessed the initiation of a number of other troughs: the east and west Carpathian and the North Balkan. The development of new geosynclinal troughs was especially intensive from the Late Cretaceous on.

All troughs, from the Triassic through the Cretaceous and Paleogene were formed along systems of deep faults which fringe them and which cut the entire Alpine folded province. They are accompanied by basic extrusives and intrusives.

At the close of the Paleogene (Oligocene) and the beginning of the Miocene, the Alpine folded province was involved in major uplifts which closed the synclinal troughs to form synclinoria. Some of the latter were involved in the uplift and became components of large anticlinoria (Caucasus) with intermontane troughs between them, such as the Greater and Lesser Hungarian, Viennese, Transylvanian, Thessalian, Thracian, Anatolian, Kars, Colchis, Kura, Araks, and smaller ones. They began to be filled up with molasse deposits. A system of marginal troughs was formed along the periphery of the Alpine folded province: Alpine, Caucasian, Carpathian, Caucasian foredeeps, etc. Deep troughs of another type came into being at the same time, those of the Black, Tyrrhenian, Mediterranean, Marmora, and Caspian seas, similar in their geophysical properties to oceanic troughs.

Thus, there are three stages in the development of the Alpine folded province: a) the early, with a development of Triassic and Lower and Middle Jurassic geosynclines; b) the late, with a development of younger and Paleogene geosynclines; and c) the terminal, with a development of intermontane and marginal troughs and those of the oceanic type.

In discussing this paper, N. S. Shatskiy, V. Ye. Khain, and A. V. Peyve noted the importance of its data for the history of the Alpine geosynclinal province and of geosynclinal provinces in general.

The discussion of tectonics was brought to a close by A. I. Suvorov's paper, "Structure and Relationship of The Two Main Types of Faults In Hercinian Rocks of Central Kazakhstan". There are two main trends of these faults, a northwestern and a northeastern, which, locally becoming more closely spaced, form extended (up to 350 km) and comparatively narrow (10 to 30 km) zones. This paper, rewritten and renamed, "The Uspensk Zone of Central Kazakhstan and Some of Its Analogues", will be published in Izvestiya Academy of Sciences, U. S. S. R., Geologic Series.

In the field of lithology, Academician A. L. Yanshin read his paper, "Some Specific Features of the Accumulation of Thick Salt Sequences". In summing up the data of a number of modern students, he pointed out that it is incorrect to regard fossil salt sections as lagunal, because they have accumulated in basins utterly unlike the present-day lagoons. In most instances, these were very large marine basins with a peculiar salt composition of their waters, differing from salts of the ocean because of their "metamorphism" in a number of intermediate basins.

The main feature of thick salt deposits is their extremely rapid deposition. Detailed petrographic studies of many Soviet and foreign deposits have demonstrated that the familiar banding in rock- and K-salts is a reflection of annual hydrochemical cycles. It was computed that salt had accumulated at an average annual rate of 6 to 8 cm (A. A. Ivanov, M. P. Fiveg, et al). Consequently, even thick salt sequences were deposited in a very short time, geologically speaking. It took but 13,000 years to deposit the Verkhnekamsk salt, 520 m thick. In uninterrupted sections beyond the salt areas, a layer of clay and marl less than one meter thick could have been deposited during the same period. This ratio of thicknesses for salt and salt-free deposits must be taken into consideration in stratigraphic correlations.

This rapid rate of salt accumulation, together with the great thickness of many salt sequences, suggests that the salt filled up some deep troughs, i. e., salt basins which were, at their initial stages, uncompensated marine basins. This is even better illustrated by the salt deposition rate as compared with that for presalt sulfate terrigenous and sulfate-carbonate rocks. The latter, too, exhibit annual stratification suggesting a deposition rate of 0. 5 to

3 mm per year. It is hardly possible that in all examples under study, the rate of subsidence increased tens of times just as halite began to be deposited. It is more probable that the thickness of salt sequences reflects, on the whole, the depth of the basin, prior to salt deposition, rather than a subsidence during it. This original depth is perhaps the determining factor for maximum depths of salt sequences which seldom reach 600 or 700 m and never exceed 1000 m.

In some examples, the great depth of salt basins is corroborated by other data, as well. Thus the Kungurian salt sequence, in a trough east of the Ishimbayevo reef zone, rests without a break on Artinskian bathyal sediments whose depth of deposition, as inferred from their thickness in the reef zone, is estimated at 800 m by I. V. Khvorova, and at 1000 to 1200 m by A. A. Bogdanov. That should be the depth of the Kungurian sea at the beginning of the salt deposition. German lithologist R. Kühn estimates the original depth of the Strassfurt salt basin at 860 m, on the basis of the bromine content in halite. All salt basins were filled up and became shallow because of the high sedimentation rate.

The popular opinion that all salt basins were always shallow is based on a dogmatic application of the actualism principle. It cannot be substantiated by any weighty physiochemical arguments.

Discussion of the A. L. Yanshin paper proceeded mostly with reference to physiochemical conditions of salt accumulation. A number of participants (B. P. Zhizhchenko, N. I. Lunin, and B. M. Keller) held that salt can be deposited in comparatively deep basins, while some others (Academician N. M. Strakhov, M. P. Fiveg) maintained that this is possible only under shallow conditions.

Following that, A. V. Kopeliovich, A. G. Kossovskaya, and V. D. Shutov reported on "Some Features in Epigenesis of Terrigenous Deposits in Platform and Geosynclinal Provinces" (to be published in Izvestiya Academy of Sciences U. S. S. R., Geologic Series).

L. N. Formozova demonstrated in her paper, "Types of Formations of Oölitic Iron-Ore Deposits" that analysis of the genesis, and more valuable in the forecasting and exploration, the classification of these ores is possibly a geologic one. The association of oölitic ores with various geologic formations is controlled by a definite geochronologic regularity. A migration of oölitic ores from one formation to another takes place in the course of geologic history, with the ores assuming their specific lithologic and mineral features, in each instance. Eight types of oölitic ore deposits have been distinguished.

I. The Thuringian, including the most ancient ores, from Rhiphean to Ordovician, developed only in eugeosynclines and associated with dark siliceous schist, shale, and volcanic rocks, with typical intercalations of phosphorite and chert. All these rocks and ores are siliceous and free of lime.

II. The Bashkirian (to be subdivided), including Silurian and Devonian miogeosynclinal and platform deposits. Its ores are associated with terrigenous-carbonate rocks, rich in alumina and commonly grading into bauxite.

III. The Khalilov, occurring only in Lower and Middle Jurassic lacustrine deposits of younger platforms, in association with argillaceous rocks derived from an ancient ultrabasic oxidized zone. These ores are rich in Ni and Cr and often free of $Al_2O_3$. They do not contain any lime or glauconite.

IV. The Lotharingian is developed in Jurassic and Lower Cretaceous marine deposits of epi-Paleozoic platforms and marginal parts of geosynclines. These ores occur in calcareous-terrigenous rocks, and are strongly calcareous and often self-fluxing.

V. The Ayat, occurring only in Upper Jurassic, Cretaceous, and Paleogene littoral-marine deposits of younger and partly of older platforms. These ores are associated with glauconitic rocks, being glauconitic themselves as well as rich in phosphorus, poor in $CaCO_3$, and never carrying free alumina.

VI. The Aralian, typical of Upper Cretaceous and Paleogene continental deposits. This ore occurs in glauconite-free areno-argillaceous non-calcareous rocks.

VII. The Atlas, observed only in Eocene rocks of the epi-Hercinian platform of Tunisia and Algeria.

VIII. The Kerch, comprising Middle Pliocene brackish-water ores of a marginal trough. They occur in sands and clays and are rich in Mn, Ba, and P.

In discussing this paper, Academicians N. S. Shatskiy, N. M. Strakhov, I. V. Khvorov, and I. M. Varentsov, considered the possibility and the method of applying formation analysis in forecasting the trend of exploration for sedimentary minerals.

This annual Session of Academic Council of the Geological Institute, besides introducing the geological fraternity to the progress of many scientific problems under consideration, also provided the opportunity for discussing the further trends of study.